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ON THE MAINTENANCE OF COMBINATIONAL VIBRATIONS BY TWO SIMPLE HARMONIC FORCES.

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Introductory.

In a previous publication in this Review[1] I dealt with my experimental investigations on a new class of forced oscillations maintained by periodic variation of spring, of which the well-known phenomenon of the maintenance of vibrations by forces of double frequency (dealt with by Faraday, Melde and Lord Rayleigh) is a specific case. Working with the same apparatus as is used for one of the forms of Melde's experiment, I showed that a simple harmonic force acting longitudinally upon a stretched string could maintain its vibrations when the frequency of the free oscillations of the string in any given mode, is sufficiently nearly equal to any integral multiple of half the frequency of the fork. To illustrate and explain the manner in which such maintenance is effected, a series of photographs were published with the paper, showing simultaneous vibration-curves of the exciting tuning-fork and the maintained motion of the string, in which the natural frequencies of the latter were various integral multiples of half the frequency of the former. From these photographs and the mathematical discussion, it became clear that a very important part in the maintenance of the motion is played by certain subsidiary components introduced into it under the action of the variable spring. The principal component of the maintained vibration together with the subsidiary motions thus introduced could, it was shown, be arranged in the form of a Fourier series, the difference of frequency between the successive terms being that of the variable spring itself.

The successful investigation of this class of resonance-vibrations suggested further experiments with systems subjected simultaneously

[1] "Some Remarkable Cases of Resonance," Physical Review, Dec., 1912.

to *two* simple harmonic forces of differing frequencies varying the spring. These have been productive of some very interesting results and will form the subject of the present paper.

EXPERIMENTAL ARRANGEMENTS.

As mentioned above, the idea underlying the investigation now to be described was to subject a system, having a frequency of vibration that could be adjusted to any desired value over a wide range, *e. g.*, a stretched string, simultaneously to two simple harmonic forces of known frequencies varying its spring, and then to observe and record the various cases in which the state of equilibrium which usually obtains becomes unstable and the system settles down into vigorous vibration.

The experimental method adopted was extremely simple. Two electrically-maintained turning-forks were used. These stood on the table at some distance apart with their prongs vertical, in one plane, and directions of vibration parallel. A fine silk or cotton string, one or two metres in length, was stretched horizontally between the two forks, its extremities being attached to one prong of each fork (*i. e.*, to those nearest to each other). The tension of the string when the forks were at rest could be readily adjusted by merely sliding one fork slightly towards or away from the other along the table. Since the prongs of the fork are vertical and the string is parallel to their direction of vibration, we have as the result when the forks are excited, that the tension of the string is periodically varied by the vibrations of both simultaneously.

Of course, with the arrangements described neither of the forks, whether acting by itself or conjointly with the other, tends *directly* to displace the string from its position of equilibrium. They vary the tension of the string, but the latter remains undisturbed so far as transverse movement is concerned, except when the initial tension, *i. e.*, the frequency of free oscillation of the string, is adjusted so as to coincide more or less accurately with certain values which we may for convenience term "resonance frequencies," leaving the justification of this phraseology to be dealt with later.

Certain of the resonance-frequencies should obviously be multiples of half the frequency of one or the other of the forks by itself. For, each of the forks acting alone can maintain a vigorous vibration in a number of cases as shown in the paper referred to above, and this vibration is excited and maintained under suitable conditions even in the presence of the other periodic force varying the spring. To put it mathematically, if the frequency of free oscillation of the string in any given

mode is sufficiently nearly equal to either $\frac{1}{2}rN_1$ or $\frac{1}{2}sN_2$, where N_1, N_2 are the frequencies of the forks, r, s, being any positive integers, we would get resonance-vibrations as already shown. That certain of the resonances observed are of this class, can readily be verified by stopping the fork which does not play a part in the maintenance, when the vibration of the other fork continues to sustain the motion of the string.

Besides the resonances of the kind described in the preceding paragraph, the observer is surprised and delighted to find, even at a first trial of the experiment, a large number of other cases of vigorous maintenance which have evidently to be ascribed to the joint action of the two forks on the string. Their variety and number is extraordinary, and these, together with the way in which they come rapidly following one another particularly at the higher frequencies, remind the observer, by a vivid analogy, of the lines in a complicated spectrum-series. It is readily guessed at once that these are cases of "combinational" resonance in which the frequency of the principal term in the maintained motion is related *jointly* to the frequencies of both the forks. This fact is readily verified by experimental investigation as described below, and the results obtained can be stated with generality thus. Under suitable conditions the equilibrium of the system becomes unstable and a vigorous motion is maintained if the frequency of free vibration in any given mode is sufficiently nearly equal to $\frac{1}{2}rN_1 \pm \frac{1}{2}sN_2$, where r and s are *positive* integers. The degree of accuracy of adjustment necessary for maintenance increases as r and s increase. Where the positive sign applies we have "summational" resonances. With the negative sign we have "differential" resonances. The frequency of the maintained motion is *exactly* equal to $\frac{1}{2}rN_1 \pm \frac{1}{2}sN_2$, where r and s have the values assigned.

Of course N_1 and N_2, which are the frequencies of the forks, do not in general stand in any simple arithmetical ratio, and the cases of "combinational" resonance described in this paper could in almost all cases be recognized and distinguished from "simple" resonance due to either of the forks acting alone by a peculiar appearance of "flicker" due to the presence of *small* components of very low frequencies in the motion. Even if this method failed, there is the alternative test of stopping either of the two forks when a "combinational" is instantly extinguished, whereas a "simple" resonance is only abolished by stopping *one* of the two forks, and not *either*. One very characteristic feature which was noticed in the experiments was that while resonance-vibrations of the *summational* class were obtained with great ease up to fairly high orders and vigorously maintained, *differential* vibrations were not nearly so readily maintained, and it was found necessary, in order to realize them

to arrange matters so that none of the other resonances due to the forks, simple or summational, lay in the neighborhood of the one sought for and could therefore extinguish it, the former being maintained by preference. The result noticed above is an inversion of the ordinary experience in acoustical work with combinational tones in which it is found that differentials are generally stronger and easier to demonstrate than summationals. The theoretical explanation of the effect will be discussed later in this paper.

PHOTOGRAPHIC RECORD OF COMBINATIONAL VIBRATIONS.

In order to demonstrate that the frequency of maintenance is that given by the combinational formula referred to above, the method of vibration-curves was used. Arrangements were made to obtain simultaneous photographic records of the vibration of the two forks and of the maintained oscillation of the string. These records incidentally throw light on the *modus operandi* of the maintenance. The disposition of the apparatus employed is shown in Fig. 1.

T_1 and T_2 are the two forks which stand with prongs vertical on the table. The string is stretched horizontally between the inner prongs of the forks as shown.

To enable its plane of vibration to be brought into the vertical at pleasure, the following very simple device is adopted. Each end of the string is attached to a loop of thread which is passed over the prong of the fork, instead of directly to the prong itself. The result of this mode of attachment is that the frequencies of vibration in the horizontal and vertical planes differ slightly, and this has the desired effect of keeping the vibration confined to the vertical if the tension of the string is suitably adjusted in each case. Immediately in front of the string is placed a camera, the plate-carrier of which has been removed, and which carries instead a square sheet fitted with a narrow vertical slit S as nearly as possible contiguous to the string. The light from an electric arc emerges from the nozzle of the lantern L; and is then divided into three parts.

1. One part passes first through the vertical slit S, then through the lens of the camera carrying it, and after suffering reflexion at the fixed mirror M passes on to the lens of the moving-plate camera DD (to be described below).

2. The second part is deflected by the mirror M_1, and after passing through a narrow horizontal slit S_1 suffers reflexion at the surface of a small plane mirror M_2 attached to the prong of the fork T_1 and is finally deflected by the mirror M_3 to the lens of the camera DD.

3. The third part after deflexion by the mirror M_4 passes through the

horizontal slit S_2, and thence after reflexion at a plane mirror M_5 attached to the prong of the fork T_2 passes on to the camera DD.

By suitably adjusting the position of the slits S_1 and S_2 and the distance between the slit S and the lens of the camera carrying it, it was found possible without the use of any additional collimating lenses to obtain

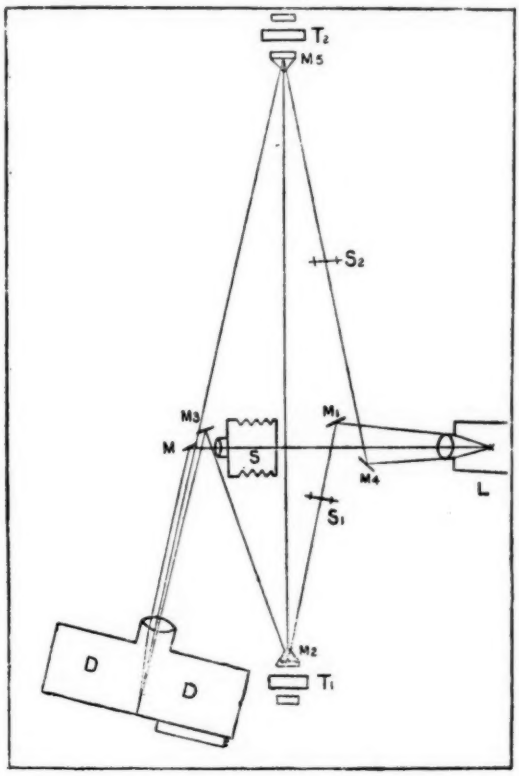

Fig. 1.

Apparatus for the production and photographic record of combinational vibrations.

in the focal plane of the camera DD real images of the vertical slit S and of the horizontal slits S_2 and S_1, the images of the latter being formed respectively above and below the images of the vertical slit S. A narrow vertical slit placed in the focal plane of the camera immediately in front of the ground-glass or its substitute, the photographic plate, cuts off everything except two brilliant spots of light, one for each fork, and between them the image of the illuminated vertical slit crossing which is seen the shadow of the string when at rest. The plate-holder can be moved (by hand) in horizontal grooves behind the slit in the focal plane, and when the forks are set in vibration we can thus obtain

photographic records of simultaneous vibration-curves of the string and forks.

By counting the number of swings shown in each of the three curves appearing in a record, the relation between the frequencies of the forks and that of the maintained motion of the string can be observed and tested with the exact combinational formula $\frac{1}{2}(rN_1 \pm sN_2)$. Illustrations of this method will be given later.

ISOLATION OF INDIVIDUAL TYPES.

As already mentioned above, the vibrations of the summational class are obtained with great ease. Taking only the first four types of summationals, *i. e.*, with $r = 1$ or 2 or 3 or 4 and $s = 1$ or 2 or 3 or 4, we have 4×4, *i. e.*, 16 distinct types possible, or if we include the cases in which either r or s is zero, *i. e.*, those of resonance due to each of the forks acting by itself, 24 distinct types. In practice summationals of types even higher than the fourth are distinguishable. For each of these various frequencies of vibration, the string may divide up into one, two, three or more ventral segments, according to circumstances. We have therefore a very large number of cases in which resonance is possible, and it is a matter for considerable surprise that it should be at all possible (not to speak of its being quite easy) to isolate in experiment any one of these manifold modes and frequencies of vibration and obtain distinctive photographic records of the same. The explanation of this result is very instructive. It rests upon the following facts: for each of these summationals there is a limited and fairly well-defined range of frequency within which the natural frequency of the system should lie if maintenance is to be possible. If the natural frequency of the system lies within this range, the vibration is vigorously maintained. If outside it, the summational does not put in an appearance. The range becomes narrower and narrower as we go higher up the scale and is smallest in the very region where the summationals are relatively speaking most numerous. This effectually prevents their crowding in unduly upon each other.

The facts mentioned in the foregoing paragraph sufficiently explain the successful isolation of the several vibrational types. After a little practice it will be found easy to arrange that any given member of the series of summationals (if not of too high an order) is obtained and vigorously maintained. The necessary guide to the proper adjustment of tension is to be had by noticing the tensions at which the "simple" resonances in various modes due to either of the forks acting alone occur, and by drawing up a table of frequencies of the summational vibrations it is a simple matter to get the right tension for any one of them.

In practical work, it will be found a useful device (besides adjusting the tension of the string to correspond with the frequency required), to regulate the amplitude of vibration of the forks in a suitable manner. This is readily done, if the forks are electrically maintained by altering the driving current or the position of the contact-maker. The formula to be borne in mind is, if r is large and s is small, to work the N_1 fork vigorously and the N_2 fork with quite a small amplitude of vibration: vice-versa if r is small and s is large. If r and s are to be nearly equal, the amplitudes are to be roughly commensurate with the values of r and s. This regulation of the amplitude ensures the desired summational being obtained without fail, and unaccompanied by other modes of vibration.

Vibration-Curves of Summationals.

Figs. 3 to 13 exhibit the photographic records for all the nine summationals comprised within the first three types, for one summational of the fourth type and one of the fifth, *i. e.*, eleven photographs in all. The two forks used had frequencies of 60 and 23.7 respectively per second. In the reproductions their vibration-curves appear white on a dark ground and that of the string dark on a bright background. The two former appear one on each side of the latter. It is obvious from an inspection of the vibration-curves of the string that in each case the principal part of the maintained motion is accompanied by subsidiary components. These components are introduced by the alteration of the character of the maintained motion due to the imposed variable spring, and it will be seen from the theoretical discussion to follow that they act as vehicles for the supply of energy to the system. In a few cases their periodicity is fairly evident to inspection.

Fig. 3.—This is the first and most important summational, the frequency of maintenance being equal to the sum of half the frequencies of the forks. This is readily shown by counting the swings shown on each curve. Thus—

Summational $\frac{1}{2}N_1 + \frac{1}{2}N_2$.

	Fork N_1.	Fork N_2.	String.
Number of swings.....	17.50	6.90	12.23
Calculated frequency.....	60.0	23.70	41.95
Observed frequency.....	60.0	23.70	41.93

An inspection of the vibration-curve of the string clearly shows the periodic flattening and sharpening of the maintained motion under the joint action of the components of the variable spring.

Fig. 4.—This shows the next higher frequency of maintenance, summational $\frac{1}{2}N_1 + N_2$, frequency 53.7 approximately.

Fig. 5 shows the summational $\frac{1}{2}N_1 + \frac{3}{2}N_2$, frequency 65.6.
Fig. 6 shows the summational $N_1 + \frac{1}{2}N_2$, frequency 71.9.
Fig. 7 shows the summational $N_1 + N_2$, frequency 83.7.
Fig. 8 shows the summational $N_1 + \frac{3}{2}N_2$, frequency 95.6.
Fig. 9 shows the summational $\frac{3}{2}N_1 + \frac{1}{2}N_2$, frequency 101.9.
Fig. 10 shows the summational $\frac{3}{2}N_1 + N_2$ frequency 113.7.
Fig. 11 shows the summational $\frac{3}{2}N_1 + \frac{3}{2}N_2$, frequency 125.6.
Fig. 12 shows one of the summationals of the fourth type, frequency $2N_1 + \frac{1}{2}N_2$, *i. e.*, 131.9.
Fig. 13 shows one of the summationals of the fifth type, frequency $2N_1 + \frac{5}{2}N_2$, *i. e.*, 179.3.

Vibration-Curves of Differentials.

Using the two forks of frequencies 60 and 23.7 it was not found possible to obtain any cases of differential resonances, as these lay in the region in which the primaries and summationals were present and were strongly maintained in preference. After some trial, however, using forks of adjustable frequencies with which the frequencies of possible differentials lay far removed from that of the stronger resonances due to either of the forks alone or their summationals, I succeeded in isolating two cases of differential resonance. Fig. 14 represents the differential of the first type, frequency $\frac{1}{2}N_1$ and $\frac{1}{2}N_2$, being respectively 128 and 23.7. Fig. 15 represents a differential of the second type, frequency $N_1 - N_2$ being 92.3, the frequencies of the two forks used, N_1 and N_2, being respectively 128 and 35.7.

It will be seen that in both of these cases, the frequency of the differential is such that it cannot be readily confused with that of any resonances due to either of the forks acting alone or to their summationals.

General Theory of Combinational Maintenance.

The equation of motion of a simple oscillatory system having one degree of freedom when subject to two periodic forces varying its spring may be written as

$$\ddot{U} + k\dot{U} + n^2U = 2U[\alpha_1 \sin 2p_1t + \alpha_2 \sin 2p_2t + \beta_1 \cos 2p_1t + \beta_2 \cos 2p_2t] \quad (1)$$

$$= U[2\gamma_1 \sin (2p_1t + E_1) + 2\gamma_2 \sin (2p_2t + E_2)]. \quad (2)$$

It may also be written in the form

$$\ddot{U} + k\dot{U} + (n^2 - 2\gamma_1 \sin \overline{2p_1t + E_1} - 2\gamma_2 \sin \overline{2p_2t + E_2})U = 0. \quad (3)$$

It is instructive to compare the equation of motion as it is written in forms (1) and (2) above, with that of an asymmetrical system subject to

double forcing considered by Helmholtz. The latter may be written as

$$\ddot{U} + k\dot{U} + (n^2 - \gamma U)U = 2\gamma_1 \sin(2p_1 t + E_1) + 2\gamma_2 \sin(2p_2 t + E_2) \quad (4)$$

or as

$$\ddot{U} + k\dot{U} + n^2 U = \gamma U^2 + 2\gamma_1 \sin(2p_1 t + E_1) + 2\gamma_2 \sin(2p_2 t + E_2). \quad (5)$$

Equations (2) and (5) are analogous in so far as the term on the right-hand side which represents the "disturbing force" acting on the system is in both cases a function of two variables, *i. e.*, the time, and the configuration of the system: the form of the function is however different in the two cases.

Equations (3) and (4) are analogous in so far as that the coefficient of the third term on the left which represents the "spring" of the system is in both cases a variable. But here the analogy ends, for in one case the variable part of the spring is an independent function of the time, in the other case it is a function of the configuration only.

In any case, however, there is abundant material to suggest that the maintenance of a series of combinational vibrations should be possible under the joint action of two periodic forces of different frequencies varying the spring, and this is fully verified by the results of the experiments described above.

Discussion of Diagram of Periodicities.

The exact process by which the maintenance of the combinational vibrations is effected in these experiments is best understood by analogy with the simpler case of oscillations under variable spring of only one periodicity, and by reference to Fig. 2. In the theory of oscillations maintained by a simple variable spring referred to above, it was shown that when resonance was secured by adjusting the natural frequency of the system to any multiple of half the frequency of the impressed force, the principal part of the maintained motion and the subsidiary components of smaller amplitudes introduced under the action of the variable spring could be arranged in the form of a Fourier series. For example, in the case of the fourth type of maintenance, the equation of motion is

$$\ddot{U} + k\dot{U} + n^2 U = 2\alpha U \sin 2pt,$$

and n being nearly equal to $4p$, we have as the solution

$$U = A_2 \sin 2pt + \mathbf{A_4 \sin 4pt} + \text{etc.}$$
$$+ B_0 + B_2 \cos 2pt + \mathbf{B_4 \cos 4pt} + \text{etc.}$$

Similarly in the case of the third type of maintenance where n is nearly equal $3p$ we have

$$U = A_1 \sin pt + \mathbf{A_3 \sin 3pt} + \text{etc.}$$
$$+ B_1 \cos pt + \mathbf{B_3 \cos 3pt} + \text{etc.}$$

It will thus be seen that in each case, the subsidiary components introduced under the action of the variable spring proceed by successive differences of $2pt$. The components having smaller frequencies than that of the system were the vehicles for the supply of energy required for the maintenance of the oscillations: those having higher frequencies play no such part, but are equivalent merely to a small alteration in the natural frequency of the system. The components of smaller frequencies are none of them negligible so far as the explanation of the maintenance is concerned: those of higher frequencies can generally (though not always) be safely ignored.

In Fig. 2 each of the points marked corresponds to a frequency of the system at which (to a close approximation) resonance is possible under the sole or joint action of the two components of variable spring in the

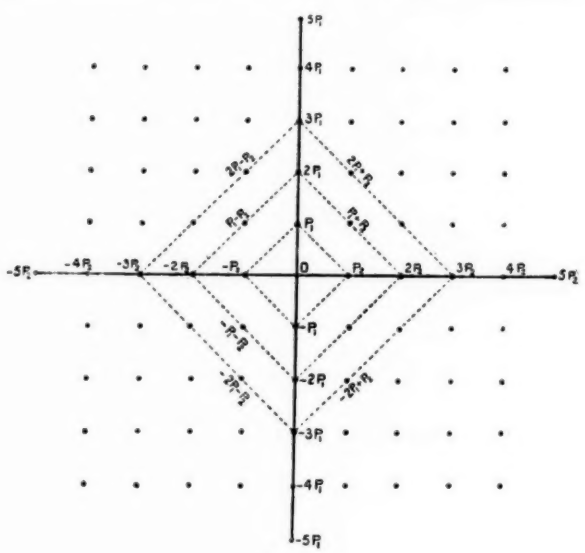

Fig. 2.

Representation of periodicities of combinational maintenance.

experiments described above. The diagram also enables us to see at a glance the periodicity of the subsidiary components in the motion in each such case. For, starting at the resonance-point for the case, we move by successive steps of $2p_1$ and $2p_2$ respectively parallel to the two axes, and each point so arrived at represents a component in the motion induced under the action of the variable spring. Only about one fourth of the total number of points in the diagram can be arrived at in this way from a given starting-point. Such of the components as are represented by points lying outside the diagonal square drawn through the

resonance-point (as in the specimens shown by dotted lines in the diagram), may be neglected in considering the maintenance of the motion. For example, when considering the case $n = (p_1 + p_2)$ nearly, only the components which are trigonometrical functions of $(p_1 + p_2)t$ and $(p_1 - p_2)t$ need be taken into account to arrive at an approximate solution. It will be seen that alternative paths starting from the same point lead to periodicities having the same value, with or without the sign reversed; and it is this fact and the negligibility of points lying outside the diagonal square in each case that enables a definite solution of the equation of motion to be obtained easily by the method of approximations.

The diagram of periodicities has other uses. It enables us to obtain at a glance an indication of the circumstances under which maintenance can be successfully effected in each case, and to arrange the experimental conditions accordingly. For instance, in the case of motion under one of the components of variable spring alone, we know that the adjustment of the natural frequency of the system with reference to that of the impressed force should be more and more accurate as we proceed outwards along the axes of the diagram and meet the successive resonance-points. In the case of the point p_1 the adjustment should be accurate to the order α, in the case of the point $2p$ to the order α^2, and so on, α being the coefficient of the variable spring (supposed small). The diagram suggests that a similar increase in the accuracy of adjustment would be found necessary as we proceed outwards from the origin in any other direction and meet resonance-points situated on successive diagonals (shown as dotted lines). This indication is amply confirmed both by experiment and by the detailed mathematical treatment. For instance it will be shown below that a degree of adjustment accurate to the order α^2 would be necessary for the point $p_1 + p_2$ which lies midway between $2p_1$ and $2p_2$.

The position of any resonance-point on the diagram is also found to indicate approximately the amplitude of vibration of the two tuning-forks required for successful maintenance.

Theory of Summationals of the First Type.

We now proceed to consider the detailed theory of the simplest summational type in which the frequency of maintenance is equal to the sum of half the frequencies of the forks. As already explained, the whole of the string behaves as one unit, in other words, we may write down the equation of motion as that of a system having only one degree of freedom. The equation is

$$\ddot{U} + k\dot{U} + n^2U = 2U[a_1 \sin 2p_1t + a_2 \sin 2p_2t + \beta_1 \cos 2p_1t + \beta_2 \cos 2p_2t]. \quad (1)$$

Since by assumption n is nearly equal to $p_1 + p_2$, we may commence building up a solution by putting

$$U = A_1 \sin (p_1 + p_2)t + B_1 \cos (p_1 + p_2)t + \text{etc.} + \text{etc.} \quad (6)$$

On substituting the first two terms on the right of (6) for U in the right-hand side of equation (1) and expanding the terms in it, we find that none of them is a sine or cosine of $(p_1 + p_2)t$, *i. e.*, represents a force which is competent to excite resonance, if we regard (1) as the ordinary equation of forced oscillations. It is obvious, therefore, that to solve the equation even approximately and explain the maintenance of the motion, we have to take a second subsidiary pair of terms in the expression for U. The frequency of these terms is ascertained at once by reference to the diagram of periodicities given above, and we may then write

$$U = A_1 \sin (p_1 + p_2)t + B_1 \cos (p_1 + p_2)t + A_2 \sin (p_1 - p_2)t + B_2 \cos (p_1 - p_2)t + \text{etc.} \quad (7)$$

The terms in A_2 and B_2 are of course small compared with those in A_1B_1, yet are sufficiently large to make their presence felt in the vibration-curve pictured previously. They are introduced by the action of *either* of the two periodic components of the variable spring on the fundamental motion, and in their turn maintain the latter by making the requisite supply of energy to the system possible. This can be shown by writing out the equation of the work supplied to the system by the variable spring and that dissipated by frictional forces in an equal time. In the present case it can be shown in a simpler way by merely equating separately the terms of various periodicities on either side of equation (1) after substituting the value of U given by (7).

We have thus:

(writing $n^2 - (p_1 + p_2)^2 = \theta_1$ and $n^2 - (p_1 - p_2)^2 = \vartheta_2$, $k(p_1 + p_2) = \phi_1$ and $k(p_1 - p_2) = \phi_2$ for brevity,

$$\theta_1A_1 - \phi_1B_1 = A_2(\beta_2 - \beta_1) + B_2(\alpha_1 + \alpha_2),$$
$$\phi_1A_1 + \theta_1B_1 = A_2(\alpha_1 - \alpha_2) + B_2(\beta_1 + \beta_2),$$
$$\theta_2A_2 - \phi_2B_2 = A_1(\beta_2 - \beta_1) + B_1(\alpha_1 - \alpha_2),$$
$$\phi_2A_2 + \theta_2B_2 = A_1(\alpha_1 + \alpha_2) + B_1(\beta_1 + \beta_2), \quad (8)$$

It will be seen that these four equations were derived by retaining only terms containing trigonometrical functions of $(p_1 + p_2)t$ and $(p_1 - p_2)t$ and neglecting all others. Before considering the effect, if

any, of the neglected terms, it is well to discuss the physical significance of the equations. They give us the three ratios A_1, B_1, A_2, B_2 in terms of the known quantities θ_1, θ_2, ϕ_1, ϕ_2, and α_1, α_2, β_1, β_2, as an approximate solution of the equation of motion and leave us in addition a relation between these "constants" which must be satisfied for steady motion to be possible.

We now proceed to solve the equations. This may, of course, be done in the usual way in terms of certain determinants, but it is more instructive to proceed by an approximate method retaining only terms up to the order of smallness desired. Assuming that α_1, α_2, β_1, β_2 (the coefficients of variable spring) are small, it is obvious from the equations that A_2, B_2 are small compared with A_1, B_1. Further ϕ_2 is a very small quantity compared with θ_2 (which is finite and large), since the former is proportional to k, the coefficient of friction, which must itself be small for maintenance to be possible. We are therefore justified in neglecting ϕ_2 and writing the last two of equations (8) thus:—

$$\begin{aligned} \theta_2 A_2 &= A_1(\beta_2 - \beta_1) + B_1(\alpha_1 - \alpha_2), \\ \theta_2 B_2 &= A_1(\alpha_1 + \alpha_2) + B_1(\beta_1 + \beta_2), \end{aligned} \tag{9}$$

These equations give us the subsidiary components of motion A_2, B_2, in terms of the principal parts A_1, B_1. Substituting these values in the first two of equations (8), we have

$$\begin{aligned} \theta_1 A_1 - \phi_1 B_1 &= \frac{A_1}{\theta_2}\Big[(\alpha_1^2 + \beta_1^2) + (\alpha_2^2 + \beta_2^2) + 2(\alpha_1\alpha_2 - \beta_1\beta_2) \Big] \\ &\quad + \frac{B_1}{\theta_2}\Big[2(\alpha_1\beta_2 + \alpha_2\beta_1) \Big] \\ \phi_1 A_1 + \theta_1 B_1 &= \frac{A_1}{\theta_2}\Big[2(\alpha_1\beta_2 + \alpha_2\beta_1) \Big] \\ &\quad + \frac{B_1}{\theta_2}\Big[(\alpha_1^2 + \beta_1^2) + (\alpha_2^2 + \beta_2^2) - 2(\alpha_1\alpha_2 - \beta_1\beta_2) \Big]. \end{aligned} \tag{10}$$

Writing

$$\begin{aligned} \theta_1 - \frac{1}{\theta_2}\Big[(\alpha_1^2 + \beta_1^2) + (\alpha_2^2 + \beta_2^2) \Big] &= \theta, \\ \frac{2}{\theta_2}(\alpha_1\alpha_2 - \beta_1\beta_2) &= a, \\ \frac{2}{\theta_2}(\alpha_1\beta_2 + \alpha_2\beta_1) &= b \end{aligned}$$

we have

$$\begin{aligned} (\theta - a)A_1 &= (\phi_1 + b)B_1, \\ (\theta + a)B_1 &= -(\phi_1 - b)A_1. \end{aligned} \tag{11}$$

The solution of this is

$$\frac{B_1}{A_1} = \frac{\theta - a}{\phi_1 + b} = \frac{b - \phi_1}{\theta + a} \tag{12}$$

and the eliminant, *i. e.*, the relation between the constants involved which must be satisfied for maintenance to be possible, is

$$\theta^2 - a^2 = b^2 - \phi_1^2. \tag{13}$$

It is interesting to consider a few special cases. For instance put

$$\beta_1 = \beta_2 = 0 \text{ and } \alpha_1 = \alpha_2 = \alpha/2.$$

From (9) we find then that

$$A_2 = 0 \text{ and } B_2 = A_1\alpha/2.$$

Also

$$\theta_1 + \frac{\phi_1^2}{\theta_1} = \alpha^2/\theta_2. \tag{14}$$

From (14) it is evident that θ_1 and ϕ_1 are both of the order α^2/θ_2, *i. e.*, both the friction and adjustment of frequency for resonance must be correct to the second order of small quantities. The equations leave the actual amplitude of the motion indeterminate. In practice both the necessary adjustment of frequency and the determinateness of the amplitude would be secured by the fact that n is not absolutely constant, in other words by the variation of spring existing in free oscillations of sensible amplitude. It will be seen that the term B_2 is small compared with A_1, since the variable part of the spring is small compared with the permanent spring: nevertheless the term B_2 plays a very important part in the maintenance of the motion, being, as is evident from the foregoing equations, the vehicle for the supply of the requisite energy to the system.

It will be seen that the equations cannot be satisfied if $\theta_1 = 0$, as $\theta_1 + (\phi_1^2/\theta_1)$ then becomes infinitely large. According to these equations therefore, resonance is possible only when θ_1 has a small but a definite positive value: *i. e.*, when the frequency of the *free* oscillations is very slightly greater than the sum of the half-frequencies of the two imposed variations of spring. This conclusion would no doubt have to be modified in view of two factors which we have not so far taken into account. First, the neglected terms in the motion which are trigonometrical functions of $(p_1 + 3p_2)t$ and $(3p_1 + p_2)t$, etc., etc. The two terms $(p_1 + 3p_2)t$, $(3p_1 + p_2)t$ which are of the order α when compared with the fundamental motion $(p_1 + p_2)t$ cannot actually assist in maintaining it. This can be shown from very simple considerations. For one thing, they are not introduced by the action of *both* the components of variable spring.

The first is due to one component and the second is due to the other. The components in the restoring force due to their action and which are trigonometrical functions of $(p_1 + p_2)t$ are in such a *phase* that their effect is equivalent to a small increase in the frequency of free oscillations of the system which is some importance when θ_1 is very small.

The second factor which we have to take into account is the variation of spring existing in free oscillations of large amplitude. This, as in the case of oscillations maintained by a single variable spring, when expanded is found to contain both constant and periodic terms. The former are equivalent to a direct increase in the natural frequency of the system, and the latter profoundly modify the effect of the impressed forces and the phases of the respective components in the motion when the amplitude is at all sensible.

THEORY OF SUMMATIONALS OF THE SECOND AND HIGHER TYPES.

As typical of the summationals of the second type we may take the case $n_1 = 2p_1 + p_2$ (nearly). The equation of motion is

$$\ddot{U} + k\dot{U} + n^2U = 2U\left[\begin{matrix}\alpha_1 \sin 2p_1t + \alpha_2 \sin 2p_2t \\ + \beta_1 \cos 2p_1t + \beta_2 \cos 2p_2t\end{matrix}\right]. \qquad (1)$$

We may to start with put

$$U = A_1 \sin (2p_1 + p_2)t + B_1 \cos (2p_1 + p_2)t + \text{etc.} + \text{etc.} \qquad (15)$$

As before, we can only solve the equation by taking certain additional terms on the right of (15). A reference to the diagram of periodicities shows that we have to take three additional pairs of terms to get an approximate solution. We may thus write

$$\begin{aligned} U = {} & A_1 \sin (2p_1 + p_2)t + B_1 \cos (2p_1 + p_2)t \\ & + A_2 \sin (2p_1 - p_2)t + B_2 \cos (2p_1 - p_2)t \\ & + A_3 \sin p_2t + B_3 \cos p_2t \\ & + A_4 \sin 3p_2t + B_4 \cos 3p_2t. \end{aligned} \qquad (16)$$

Of course, the terms in A_1 and B_1 are the largest in amplitude. In substituting the right-hand side of (16) for U in equation (1) and writing down in the results, we may use the following abbreviations:

$$\begin{aligned} n^2 - (2p_1 + p_2)^2 &= \theta_1, & k(2p_1 + p_2) &= \phi_1, \\ n^2 - (2p_1 - p_2)^2 &= \theta_2, & k(2p_1 - p_2) &= \phi_2, \\ n^2 - p_2^2 &= \theta_3, & kp_2 &= \phi_3, \\ n^2 - 9p_2^2 &= \theta_4, & 3kp_2 &= \phi_4. \end{aligned} \qquad (17)$$

By equating the various sine and cosine terms on either side of (1) after substitution, we have

$$\theta_1 A_1 - \phi_1 B_1 = \beta_1 A_3 + \alpha_1 B_3 + \beta_2 A_2 + \alpha_2 B_2,$$
$$\phi_1 A_1 + \theta_1 B_1 = -\alpha_1 A_3 + \beta_1 B_3 - \alpha_2 A_2 + \beta_2 B_2,$$
$$\theta_2 A_2 - \phi_2 B_2 = \beta_2 A_1 - \alpha_2 B_1 - \beta_1 B_3 + \alpha_1 B_3,$$
$$\phi_2 A_2 + \theta_2 B_2 = \alpha_2 A_1 + \beta_2 B_1 + \alpha_1 A_3 + \beta_1 B_3,$$
$$\theta_3 A_3 - \phi_3 B_3 = \beta_1 A_1 - \alpha_1 B_1 - \beta_1 A_2 + \alpha_1 B_2 + \beta_2 A_4 - \alpha_2 B_4,$$
$$\phi_3 A_3 + \theta_3 B_3 = \alpha_1 B_1 + \beta_1 B_1 + \alpha_1 A_2 + \beta_2 B_2 + \alpha_2 A_4 + \beta_2 B_4,$$
$$\theta_4 A_4 - \phi_4 B_4 = \beta_2 A_3 + \alpha_2 B_3,$$
$$\phi_4 A_4 + \theta_4 B_4 = -\alpha_2 A_3 + \beta_2 B_3. \qquad (18)$$

From the last four equations in (18) it will be seen that a further simplification can be effected. For A_4 and B_4 are of the order α_2, β_2 in comparison with A_3 and B_3, and the terms $\beta_2 A_4$, $\alpha_2 B_4$, $\alpha_2 A_4$ and $\beta_2 B_4$ on the right-hand side of the fifth and sixth equations in (18) can therefore be neglected in comparison with all other terms involved. We are therefore finally left with six equations only

$$\theta_1 A_1 - \phi_1 B_1 = \beta_1 A_3 + \alpha_1 B_3 + \beta_2 A_2 + \alpha_2 B_2,$$
$$\phi_1 A_1 + \theta_1 B_1 = -\alpha_1 A_3 + \beta_1 B_3 - \alpha_2 A_2 + \beta_2 B_2,$$
$$\theta_2 A_2 - \phi_2 B_2 = \beta_2 A_1 - \alpha_2 B_1 - \beta_1 A_3 + \alpha_1 B_3,$$
$$\phi_2 A_2 + \theta_2 B_2 = \alpha_2 A_1 + \beta_2 B_1 + \alpha_1 A_3 + \beta_1 B_3,$$
$$\theta_3 A_3 - \phi_3 B_3 = \beta_1 A_1 - \alpha_1 B_1 - \beta_1 A_2 + \alpha_1 B_2,$$
$$\phi_3 A_3 + \theta_3 B_3 = \alpha_1 A_1 + \beta_1 B_1 + \alpha_1 A_2 + \beta_1 B_2. \qquad (19)$$

These equations contain only terms having three periodicities, *i. e.*, the principal part of the maintained motion of frequency $(2p_1 + p_2)/2\pi$ and two others, subsidiary to it, which are given by the two nearest admissible points on the periodicity diagram, *i. e.*, of frequencies $(2p - p_2)/2\pi$ and $p_2/2\pi$ respectively. These components are derived from the principal motion by the action on it of the variations in spring, and serve to maintain it permanently in the presence of dissipative forces. They are both small compared with the main motion provided α_1, α_2, β_1, β_2, are small. Fig. 6 represents the vibration curve of this type of summational, and the component of frequency $p_2/2\pi$ (*i. e.*, half that of the graver fork) is very obvious to inspection.

Equations (19) when solved give us values for the five ratios B_1/A_1, B_2/A_1, B_3/A_1, A_2/A_1 and A_3/A_1 and leave us in addition a relation between the "constants" involved in the equations which must be satisfied for

steady maintenance to be possible. The solution of the equations by the method of determinants is really a formidable business and is in fact unnecessary: an approximate method of solving them may be used which gives results quite as accurate as the equations themselves. We notice that A_2, B_2, A_3, B_3 are small quantities relatively to A_1, B_1, and further, since k, the coefficient of friction, is necessarily very small for maintenance to be possible, the quantities ϕ_2, ϕ_3 are negligible in comparison with θ_2 and θ_3. The first step in solving the equations (19) is therefore to simplify the last four of them and obtain approximate values for A_2, B_2, A_3, B_3.

We thus have

$$\theta_2 A_2 = \beta_2 A_1 - \alpha_2 B_1 + \frac{1}{\theta_3}\left(\overline{\alpha_1^2 - \beta_1^2} A_1 + 2\alpha_1\beta_1 B_1\right),$$

$$\theta_2 B_2 = \alpha_2 A_1 + \beta_2 B_1 + \frac{1}{\theta_3}\left(2\alpha_1\beta_1 A_1 - \overline{\alpha_1^2 - \beta_1^2} B_1\right),$$

$$\theta_3 A_3 = \beta_1 A_1 - \alpha_1 B_1 + \frac{1}{\theta_2}\left(\overline{\alpha_1\alpha_2 - \beta_1\beta_2} A_1 + \overline{\alpha_1\beta_2 + \alpha_2\beta_1} B_1\right),$$

$$\theta_3\beta_3 = \alpha_1 A_1 + \beta_1 B_1 + \frac{1}{\theta_2}\left(\overline{\alpha_1\beta_2 + \alpha_2\beta_1} A_1 - \overline{\alpha_1\alpha_2 - \beta_1\beta_2} B_1\right). \quad (20)$$

The equations give us the values of the subsidiary components of motion in terms of the principal part and of the coefficients of the variable spring by which they are produced.

Substituting these values in the first two of equations (19) we have

$$\theta_1 A_1 + \phi_1 B_1 = \frac{A_1}{\theta_2\theta_3}\left[\theta_2(\alpha_1^2+\beta_1^2) + \theta_3(\alpha_2^2+\beta_2^2) + 2\beta_2(\alpha_1^2-\beta_1^2) + 4\alpha_2\alpha_1\beta_1\right]$$
$$+ \frac{B_1}{\theta_2\theta_3}\left[4\beta_2\alpha_1\beta_1 - 2\alpha_2(\alpha_1^2 - \beta_1^2)\right],$$

$$\phi_1 A_1 + \theta_1 B_1 = \frac{A_1}{\theta_2\theta_3}\left[4\beta_2\alpha_1\beta_1 - 2\alpha_2(\alpha_1^2 - \beta_1^2)\right]$$
$$+ \frac{B_1}{\theta_2\theta_3}\left[\theta_2(\alpha_1^2+\beta_1^2) + \theta_3(\alpha_2^2+\beta_2^2) - 2\beta_2(\alpha_1^2-\beta_1^2) - 4\alpha_2\alpha_1\beta_1\right]. \quad (21)$$

Writing

$$\theta_1 - \frac{1}{\theta_2\theta_3}\left[\theta_2(\alpha_1^2 + \beta_1^2) + \theta_3(\alpha_2^2 + \beta_2^2)\right] = \theta,$$

$$\frac{1}{\theta_2\theta_3}\left[2\beta_2(\alpha_1^2 - \beta_1^2) + 4\alpha_2\alpha_1\beta_1\right] = a,$$

$$\frac{1}{\theta_2\theta_3}\left[4\beta_2\alpha_1\beta_1 - 2\alpha_2(\alpha_1^2 - \beta_1^2)\right] = b,$$

equations (21) may be put into the form

$$(\theta - a)A_1 = (\phi_1 + b)B_1,$$
$$(\theta + a)B_1 = -(\phi_1 - b)A_1. \tag{22}$$

It will be seen that equations (22) are identical in *form* with equations (11) obtained for the summational of the first type and the further discussion must proceed on much the same lines.

The solution is

$$\frac{B_1}{A_1} = \frac{\theta - a}{\phi_1 + b} = \frac{b - \phi}{\theta + a} \tag{23}$$

and the eliminant is

$$\theta^2 - a^2 = b^2 - \phi_1^2. \tag{24}$$

We may as before consider the special case in which $\beta_1 = \beta_2 = 0$ and $\alpha_1 = \alpha_2 = \alpha$

$$\theta_2 A_2 = -\alpha B_1 + \alpha^2 A_1/\theta_3,$$
$$\theta_2 B_2 = \alpha A_1 - \alpha^2 B_1/\theta_3,$$
$$\theta_3 A_3 = -\alpha B_1 + \alpha^2 A_1/\theta_2,$$
$$\theta_3 B_3 = \alpha A_1 - \alpha^2 B_1/\theta_2,$$
$$\frac{B_1}{A_1} = \frac{\theta_1\theta_2\theta_3 - \alpha^2(\theta + \theta_3)}{\phi_1\theta_2\theta_3 - 2\alpha^3} = \frac{-2\alpha^3 - \phi_1\theta_2\theta_3}{\theta_1\theta_2\theta_3 - \alpha^2(\theta_2 + \theta_3)},$$
$$[\theta_1\theta_2\theta_3 - \alpha^2(\theta_2 + \theta_3)]^2 = 4\alpha^6 - \phi_1^2\theta_2^2\theta_3^2. \tag{25}$$

For maintenance to be theoretically possible in this case, the frictional coefficient k should be of the third order of small quantities and the adjustment of frequency must therefore be accurate up to the same order.

Cases of summationals of higher orders can be worked out in a similar manner, the approximation being carried to a higher and higher degree as we rise up the series.

THEORY OF DIFFERENTIALS.

The solution of the equation of motion in the case of the first differential is obviously to be obtained in this case by merely writing A_1, B_1, θ_1, ϕ_1 for A_2, B_2, θ_2, ϕ_2 and vice versa, in equations (8) obtained for the summational of the first type. We thus have

$$\theta_1 A_1 - \phi_1 B_1 = A_2(\beta_2 - \beta_1) + B_2(\alpha_1 - \alpha_2),$$
$$\phi_1 A_1 + \theta_1 B_1 = A_2(\alpha_1 + \alpha_2) + B_2(\beta_1 + \beta_2),$$
$$\theta_2 A_2 - \phi_2 B_2 = A_1(\beta_2 - \beta_1) + B_1(\alpha_1 + \alpha_2),$$
$$\phi_2 A_2 + \theta_2 B_2 = A_1(\alpha_1 - \alpha_2) + B_1(\beta_1 + \beta_2), \tag{26}$$

where

$$U = A_1 \sin (p_1 - p_2)t + B_1 \cos (p_1 - p_2)t + A_2 \sin (p_1 + p_2)t + B_2 \cos (p_1 - p_2)t + \text{etc.} \quad (27)$$

and

$$\theta_1 = n^2 - \overline{p_1 - p_2}^2, \quad \theta_2 = n^2 - \overline{p_1 + p_2}^2,$$

$$\phi_1 = k(p_1 - p_2) \text{ and } \phi_2 = k(p_1 + p_2).$$

Proceeding as before, we put

$$\theta_2 A_2 = A_1(\beta_2 - \beta_1) + B_1(\alpha_1 + \alpha_2),$$

$$\theta_2 B_2 = A_1(\alpha_1 - \alpha_2) + B_1(\beta_1 + \beta_2), \quad (28)$$

$$\theta_1 A_1 - \phi_1 B_1 = \frac{A_1}{\theta_1}\left[(\alpha_1^2 + \beta_1^2) + (\alpha_2^2 + \beta_2^2) - 2(\alpha_1\alpha_2 + \beta_1\beta_2) \right] + \frac{B_1}{\theta_2}\left[2(\alpha_1\beta_2 - \alpha_2\beta_1) \right],$$

$$\phi_1 A_1 + \theta_1 B_1 = \frac{A_1}{\theta_2}\left[2(\alpha_1\beta_2 - \alpha_2\beta_1) \right] + \frac{B_1}{\theta_2}\left[(\alpha_1^2 + \beta_1^2) + (\alpha_2^2 + \beta_2^2) + 2(\alpha_1\alpha_2 + \beta_1\beta_2) \right]. \quad (29)$$

It will be seen that equations (29) are of the same general form as (10) with certain modifications. The terms on the right-hand sides of (10) and (29) can be derived from each other by writing α_2 for $-\alpha_2$ and vice versa. The further reduction of equations (29) may be proceeded with in the usual way.

The outstanding feature of the differential types is the relative difficulty of isolating and maintaining them successfully. No doubt this is partly due to the fact that the differentials of any given order are of much lower frequency than the summationals of the same order, and they lie therefore generally in the very region of frequencies in which simpler types of resonance are maintained far more powerfully over wide ranges. These latter are maintained by preference and extinguish the differentials. The foregoing however does not appear to be a complete explanation. Possibly the following further considerations must also be taken into account in explaining the relative poverty of differentials. In the mathematical discussion, it was shown that the subsidiary components of motion introduced under the action of the variable spring, themselves enabled the principal motion to be maintained, and the relative amplitudes and phases of these components were determined on the assumption that n^2, the free spring of the system, was a constant. It was however indicated that in practice this was not strictly the case,

and in fact the success or otherwise of the experiments, *i. e.*, the steady maintenance of vibration in a certain amplitude, is dependent on the quantity n^2 not being itself absolutely a constant. For large displacements n^2 is greater than for small displacements and the equation of motion when modified to take account of this fact may be written thus,

$$\ddot{U} + k\dot{U} + [n^2 + mU^2 - \overline{2\alpha_1 \sin 2p_1 t + \beta_1 \cos 2p_1 t} - \overline{2\alpha_2 \sin 2p_2 t + \beta_2 \cos 2p_2 t}]U = 0. \quad (30)$$

The quantity mU^2 has been added to the third term within the brackets to represent the increase of spring for large displacements in a *symmetrical* system. It is obvious that when expanded for any periodic solution of U, mU^2 will give us both constant and periodic terms. The latter, *i. e.*, the periodic terms, would be of various frequencies, and of them the most important would be those which are sines or cosines of $2p_1 t$ or $2p_2 t$, since they would directly modify the action of the components of the variable spring. It is therefore quite evident that the amplitudes and phases of the subsidiary components of motion would not be the same as when mU^2 is omitted. Some components would tend to increase at the expense of others. Instances of such action have already been furnished in my previous publications when discussing maintenance by a simple variation of spring.

What we may expect to find is that when mU^2 is taken into account in the equation of motion, the subsidiary components which maintain differentials are less effective than they would otherwise be, whereas, in the case of summationals, they would be more effective. For, in the former case, some of them at least are of frequency higher than that of the maintained motion, in the latter they are invariably less, and the components of lower frequencies are encouraged at the expense of those of higher frequencies.

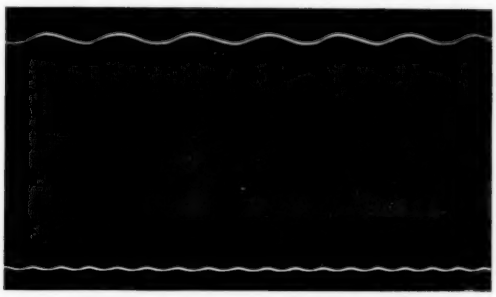

FIG. 3.

FIG. 4.

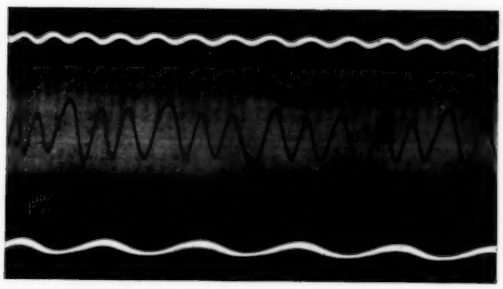

FIG. 5.

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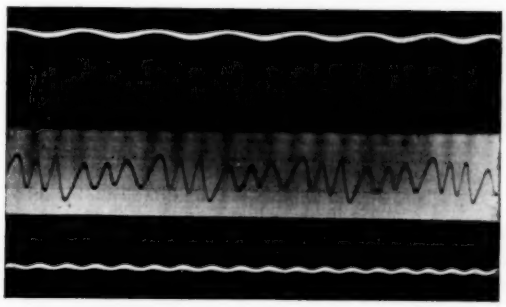

FIG. 6.

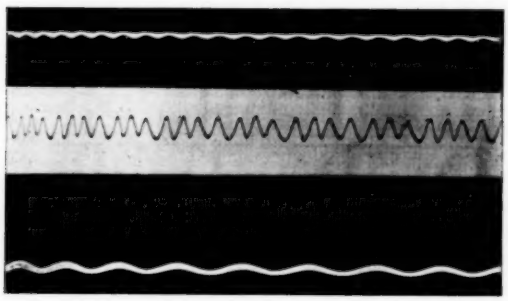

FIG. 7.

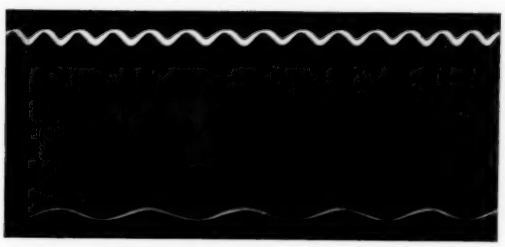

FIG. 8.

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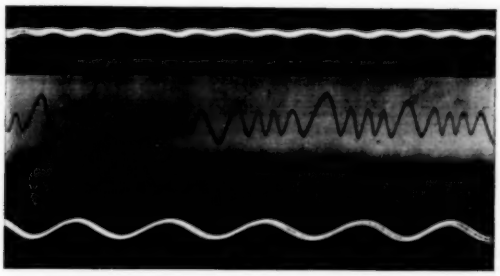

FIG. 9.

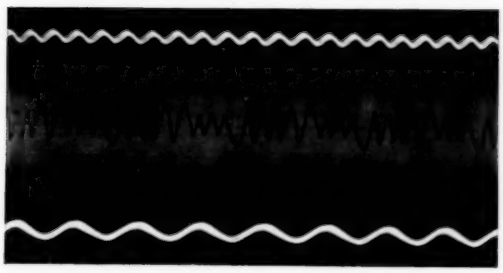

FIG. 10.

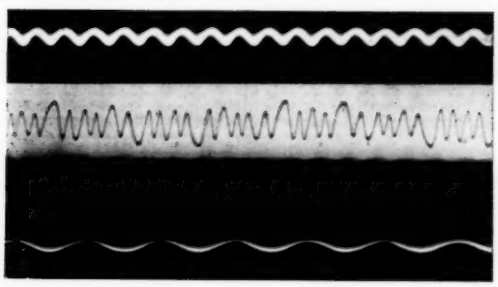

FIG. 11.

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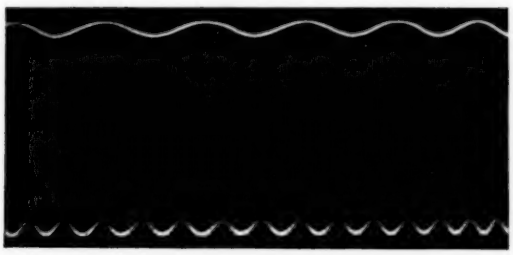

FIG. 12.

FIG. 13.

FIG. 14.

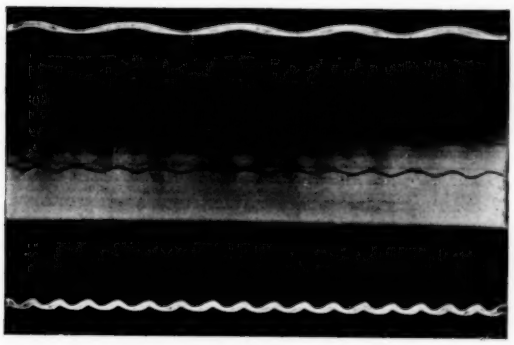

FIG. 15.

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RESISTANCE OF CARBON CONTACTS IN THE SOLID BACK TRANSMITTER.

By A. L. Clark.

IN a previous paper,[1] I have described experiments which show the time relations of resistance of carbon contacts. The following paper describes the application of the work of the first paper to some phenomena observed in ordinary solid back telephone transmitters, and continues the work of the previous paper.

While it seems hardly possible that the phenomena described below have escaped notice, no account of them has been discovered in the available literature. That the resistance of such transmitters varies with the time and applied electromotive force has been known ever since such transmitters have been used, but the cause of these variations as well as their astonishing regularity have not been adequately discussed—at least not to the knowledge of the writer. They are generally regarded as of a more or less erratic and uncertain character.

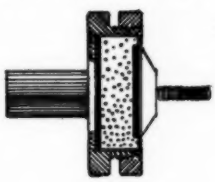

Fig. 1.

The essentials of transmitter of the so-called solid back type, with diaphragm and mouth-piece omitted, are shown in Fig. 1. The instrument consists of a cylindrical brass capsule, having one end closed and the other open. The cylindrical wall is covered inside with a thin layer of insulating material (usually paper), and the bottom is covered with a disk of carbon securely attached to the brass end of the capsule. The other end of the capsule is covered with a second carbon disk, mounted on a thin mica plate and held in place by a brass ring which is screwed on to the barrel of the capsule so that it bites the edge of the mica plate. The capsule is nearly full of carbon grains, which close the electrical circuit between the two carbon disks. The mica mounted disk is attached to the diaphragm of the transmitter and vibrates with it, when it is acted upon by sound waves, and thus alternately compresses and releases the carbon grains. The changes in contact pressure thus produced cause great changes in the electrical resistance of the system, resulting in the variations of current strength necessary for the transmission of sounds in practical telephony.

[1] Physical Review (2), I., 50, 1913.

If a solid back transmitter whose front disk is given sufficient elastic freedom of motion, is placed in an electrical circuit where the potential difference between its plates is a few volts, the following phenomena are observed. The resistance rises at first—in some cases as much as 100 per cent. or more—and then falls off more slowly. The rapidity of the rise in the earlier part of the experiment as well as the amount of rise, and later, the rapidity of the fall in resistance depend on the current density through the apparatus, being greater for large currents than for small. Fig. 2 shows the changes in resistance with time. It will be seen that the initial value of the resistance is largely a matter of accident, depending on the arrangement of the grains and the pressure with which they are held together. The time is given in seconds and the resistance in ohms. This is true for all the curves showing time relations.

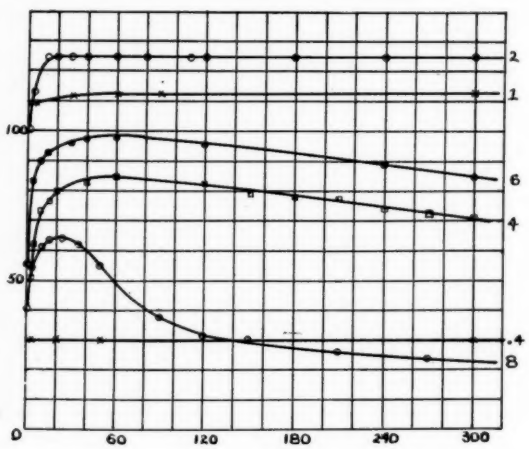

Fig. 2.

The explanation of the phenomena observed above is as follows: In the upper part of the transmitter, the current passes between points in loose contact[1] while in the lower part the contacts are tight. According to the results of my previous experiments the resistance of the contacts in the upper part of the capsule is increased when the current passes, while in the lower part there is very little change. Consequently, when the current is first turned on, the resistance rises; but after a certain time the heating of the granules causes increased pressure and shifting of points of contact which reduces the resistance again. No doubt a part of this later decrease is due to the fact that the temperature coefficient of carbon is negative. Thus we have two causes operating together; viz. the increase due to the loose contact effect and the increase of pressure

[1] Loc. cit.

due to expansion. The former predominates at first, but is overtaken by the latter. If the transmitter be jarred during the observation (see Fig. 11), the resistance drops back to nearly its initial value and the changes in resistance occur over again. This will be discussed again later on.

The phenomena have an additional complication when the carbon granules are enclosed in a capsule all of whose walls are rigid. This rigidity may be effected by clamping so that the front mica disk is held firmly, or this disk may be held with wax. In this case the points of contact which are suddenly heated by the current, expand, causing an increase in pressure between the grains, giving rise to a rapid decrease in resistance. This initial rise is soon overtaken by the increase of loose contact resistance which in turn is overtaken by the expansion due to the general rise in temperature (see Fig. 3). The initial decrease in resistance which appears when the ends of the capsules are rigidly held is seldom noticed in the ordinary use of the transmitter, because the elasticity of the mica plate holding the front carbon disk, does not allow the pressure to increase so rapidly. In other words, in the ordinary use of the transmitter, the loose contact resistance *increases* so much more rapidly than the *decrease* due to the expansion of the points, that the resistance rises instead of falls. Fig. 3 shows the manner in which the resistance changes when both disks are rigidly held. Occasionally, even in the ordinary use of the transmitter, where the mica mounting is not sufficiently elastic, there is a trace of the initial decrease.

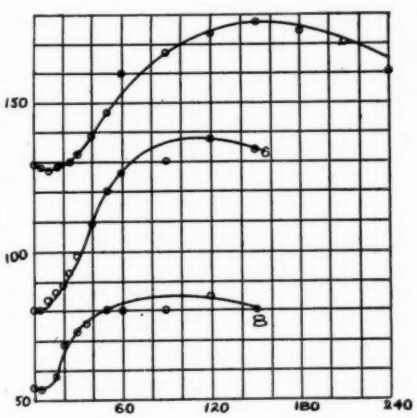

Fig. 3.

The method employed in the measurement of the resistance was a simple ammeter-voltmeter method, with dead-beat instruments which were read at short intervals. The transmitter was connected directly to a storage battery so that the applied E.M.F. remained constant.

That the sudden expansion of the grains mentioned above actually occurs was shown by the following experiment. The capsule was rigidly mounted in a clamp so that as a whole it was immovable and an optical lever with a very short arm was attached to the front disk. The current was turned on and the expansion noted with a telescope and scale. The system was arranged so that the magnification was about one thousand.

Fig. 4 shows the expansion with the time. The ordinates are thousandths of millimeters.

It will be noticed that the expansion is most rapid at the beginning and appears soon enough to make the explanation of the initial drop in the curves of Fig. 3 acceptable.

Whether we will have the curves of Fig. 2 or 3, depends upon the rigidity of the support of the carbon disk. If the rigidity is not too great, the increase in pressure is not great enough to give a droop to the curve. If the rigidity is increased, the increase in resistance may not be rapid enough to overcome the tendency to droop, so occasionally we find a transmitter where the droop sometimes appears, and sometimes does not.

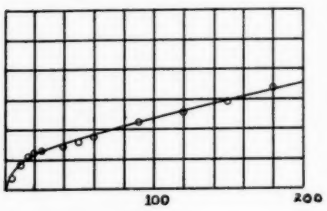

Fig. 4.

When very coarse grains are used the influence of individual contacts becomes so marked that accurate readings of current cannot be taken. Occasionally with very coarse grains such as number 16, the resistance rises rapidly to a very high value which shows that in such a case the majority of the contacts are loose. With grains as fine as number 80, the effect observed is statistical and no trouble is experienced in the readings. The grains and disks used in these experiments were obtained from the Canadian National Carbon Company, which kindly furnished grains of various sizes as well as disks with different degrees of polish.

To return to the curve of Fig. 2. That the explanation of the initial rise in resistance is correct was shown as follows: A capsule was made of a hollow brass cylinder and a carbon disk stuck on to the back with sealing wax insulating it from the brass, and the front was covered with the ordinary mica-mounted disk. A stiff copper wire P (see Fig. 5) was soldered to the middle of this disk to convey the current and small wires M and N soldered to its top and bottom. These last wires were connected to a galvanometer through a resistance box. This box was placed in the circuit to control the deflection of the galvanometer.

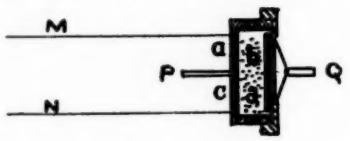

Fig. 5.

Thus the galvanometer may be used to measure the P.D. between top and bottom of the disk to which they are connected. A battery and ammeter were connected to P and Q.

It will be seen from the diagram of connections that we have virtually a Wheatstone Bridge arrangement. Let *abcd* refer to the various parts of the net representing in each case the resistance of the part on which the letter is found. The upper and lower parts of the larger disk of the capsule, a and c are divided from each other by the leading wire. The upper and lower parts of the carbon grains b and d are divided at the same place. The front disk of the capsule takes the current from all over its face and the resistance of the brass conducting layer is too small to be taken into consideration.

Let E be the constant applied E.M.F. between P and Q, I the total current measured by the ammeter, and V the potential difference between the top and bottom of the fixed carbon disk, shown by the galvanometer. The problem is to determine how the resistance of b and d affect the values of I and V (actually I/V).

Now

$$i_{ab} = \frac{E}{a+b} \text{ and } \quad i_{cd} = \frac{E}{c+d}$$

So

$$I = i_{ab} + i_{cd} = E\left(\frac{a+b+c+d}{(a+b)(c+d)}\right).$$

The drops in potential on a and c are

$$V_a = \frac{Ea}{a+b}, \quad V_c = \frac{Ec}{c+d} \text{ and } \quad V_a - V_c = V = E\left(\frac{a}{a+b} - \frac{c}{c+d}\right)$$

so finally

$$\frac{I}{V} = \frac{a+b+c+d}{ad-bc}.$$

Now if $a/c < b/d$ the current is from ab to cd or down on the figure. If $(a/c) > (b/d)$ the current is up.

In general b is larger than d, while a and c are nearly equal, so that if the capsule is turned over, d becomes larger than b and the current in the galvanometer is reversed. If a and c are unequal the current may not reverse.

Now $\dfrac{\partial(I/V)}{\partial b} = \dfrac{ad+ac+c^2+cd}{(ad-bc)^2}$ which is always positive, or an increase in the value of b causes an increase in I/V.

In the same way

$$\frac{\partial(I/V)}{\partial d} = -\frac{c+bd+cd+d^2}{(ad-bc)^2}$$

which is always negative or an increase in d causes a decrease in the value

of I/V. Fig. 6 shows the way in which I/V changes with the time. It will be noticed that I/V increases to a maximum and then diminishes.

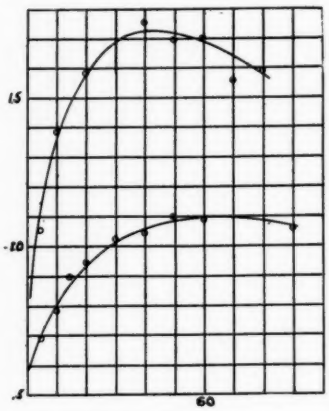

Fig. 6.

So the initial rise in the value of I/V is due to either an increase in b or a decrease in d. If due to the latter I should increase also, which is not the case. So the first change in I/V must be due to an increase in b or the loose contact effect in the upper half of the transmitter.

The decline in I/V after the maximum value is due to either a decrease in b or an increase in d, if due to the former it is caused no doubt by crowding of the grains with shifting, thus presenting new points of contact. If the decrease in I/V is due to an increase in d, it is caused by the loose contact effect extending into the lower part of the transmitter. Probably the latter cause operates first as the current does not begin to rise until after the maximum in I/V. The inequality of a and c are brought out in the two curves of Fig. 6. They represent the value of I/V for the two positions of the transmitter.

Fig. 7 shows the effect on the resistance due to changing the E.M.F. from 2 to 4 volts and back again. The two sets of curves, which can be distinguished easily, are for changes after long and short runs respec-

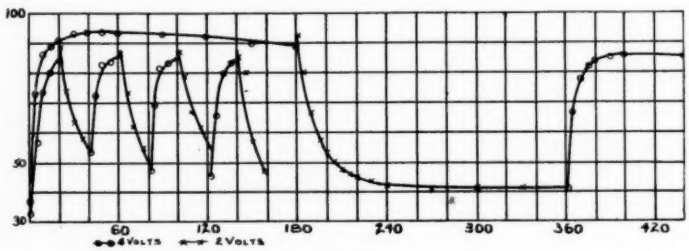

Fig. 7.

tively. It will be noticed that an increase in current is always followed by an increase in resistance and a decrease in current by decrease in resistance. The reason for the decrease in resistance is probably due to the shifting of the grains with the falling temperature. It has been proved beyond all question that a very slight change only in the position of contacts on the grains is necessary for restoration of the initial conductivity after the loose contact effect has occurred.

The recovery of the transmitter after a run was investigated as follows:

The exciting current was passed through the transmitter for a definite interval and then broken, and the circuit completed again with an exceedingly small current passed through the transmitter in series with a low range milammeter. A double-pole commutator made it possible to connect the transmitter in either circuit at will without loss of time. A resistance box was afterwards substituted for the transmitter and the readings of the milammeter reduced to ohms by substitution. Curve 1 of Fig. 2 shows that the resistance of a transmitter is practically constant when a very weak current is sent through it; so this method is applicable. Of course, the actual resistance of the transmitter depends on the current so that the value of the resistance measured with a small current is not the same as when the current is larger. However, the changes in resistance can be followed perfectly satisfactorily. Fig. 8 shows two

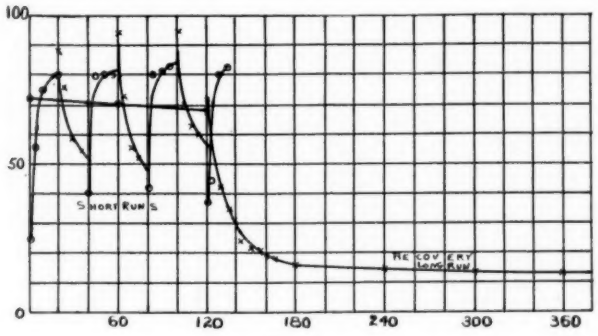

Fig. 8.

sets of curves. These curves are of long and short runs. In the case of a system of carbon grains, enclosed in a capsule with rigid walls or in an ordinary transmitter capsule where the front disk is clamped or fastened in any other way, the recovery after a run is somewhat different. The resistance rises rapidly at first and then falls off as in the case just explained. No doubt this is due to the release of the pressure due to contraction attending the rapid cooling of the points of contact.

If the pressure on the grains be increased in any way, such as by pressing on the mica-mounted disk, the resistance of the transmitter falls but quickly begins to rise again owing to the increased current. If the pressure be released, the resistance always rises but falls again immediately (see Fig. 9). The pressure was applied by pressing on the diaphragm of the transmitter with a small bristle brush.

So we see that an ordinary solid back transmitter as commonly used is a partially conservative system, as far as its resistance is concerned. Anything which causes an increase in current is met by an increase in

resistance which cuts down the current; while if the current be decreased in any way the resistance decreases, causing an increase of the current.

The question, whether or not the changes in resistance which occur with increase or decrease of pressure on the diaphragm take place quickly enough to affect the wave form when the transmitter is used in ordinary telephony, was examined, with the result that except possibly for sounds of very low pitch there can be little or no distortion due to the kind of changes just mentioned. The method employed in deciding this point was as follows: A small car on well-made wheels was arranged to run down an incline on a smooth track, dragging a brass spring brush on one of the rails, which was covered with paper, except for a small interval near the lower end. In this way the car made a momentary contact with the rail which allowed the current to pass through the transmitter for a brief interval. This interval could be varied by changing the inclination of the track. The length of the interval was determined by switching the current through the pen circuit of a drum chronograph. After the passage of the momentary current, the resistance of the transmitter was measured as in the experiment on recovery. The procedure was as follows: The resistance was first measured using the small current.

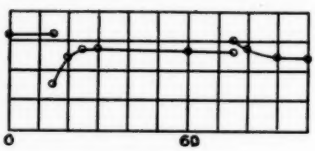

Fig. 9.

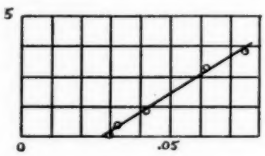

Fig. 10.

Next the car was allowed to run down making the contact through the transmitter, then allowed to run down making the same contact for the chronograph, and finally the resistance of the transmitter measured again. These operations were repeated for various inclinations. The results are shown in Fig. 10. The ordinates show increase in resistance in tenths of ohms. It will be noticed that the curve crosses the axis at about .03 seconds, which is the longest time for which no change in resistance could be noted. In all probability this curve is tangent to the horizontal axis at the origin but no measurable change in resistance occurred for a time less than .03 seconds. Thus we may conclude that the effect on the wave form is probably of no importance. Fig. 11 shows the effect of jarring the transmitter during the run as well as during the recovery.

There is no evidence of a secular change in resistance when the transmitter is used continuously over a long interval of time. On the contrary,

an experiment carried out for several days showed no sure change in resistance. A circuit breaker was arranged to make the current for 10 seconds once every minute and at the end of 48 hours the resistance curve was almost identical with the curve at the beginning of the experiment.

That the gas in which the transmitter grains are placed exercises a marked effect on their contact resistance is shown by the following experiment. A transmitter capsule with a number of small orifices in the brass back and grooves in the back of the carbon disk to allow circulation of the gas, was placed in a receiver from which the gas could be removed by pump. With air in the receiver the resistance curves

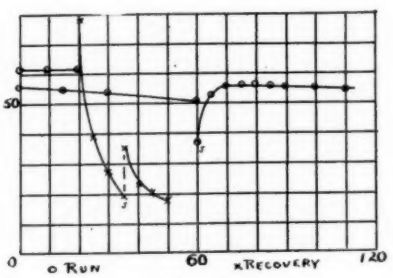

Fig. 11.

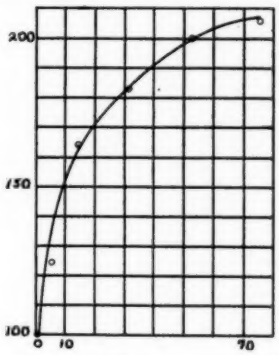

Fig. 12.

were those of Fig. 2. Also see Curve 1, Fig. 13. When the air was pumped out the curves became like those of Fig. 3 (Curve 2, Fig. 13). When the air is removed so that the pressure is about 3 mm. the rise in resistance due to the loose contact effect is very small and the droop in the curve due to the sudden expansion becomes noticeable. As soon as the air was re-admitted the curve went back to the Curve 1 class. In some of the trials the apparatus stood for several hours before measurements were taken in order that there should be no doubt that the air pressure inside the capsule was the same as the pressure in the receiver. Fig. 12 shows the relation between the resistance of a transmitter and the air pressure. One thing that should be noticed is that at any given pressure the resistance is decreased by the passage of current which indicates that the escape of the air is facilitated by the heat generated at the points of contact. This effect was noticed in the previous experiments on carbon resistance.

The effect of filling the receiver with oxygen is suggestive. When the transmitter is filled with oxygen the resistance curve rises with much greater rapidity and much higher than when it is filled with air and there is no trace of the droop in the curve shown in Fig. 3. Here the resistance

increases so rapidly that the inclination is much sharper than with air. This supports the suggestion made in the previous paper that the rise in resistance, in part at least, may be due to actual combustion with the formation of an ash or other material of permanently high resistance. Curve 3, Fig. 13 shows the resistance of an oxygen-filled transmitter. These experiments indicate that the gas at points of contact exercises more influence than usually believed.

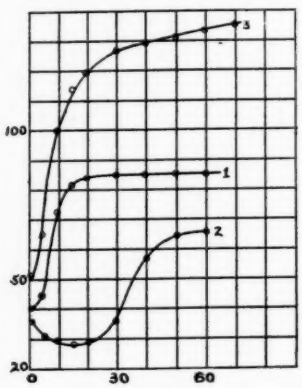

Fig. 13.

Thus far the work described has been on a transmitter which is kept perfectly quiet. The effect of a sound on the resistance of the transmitter is interesting. An ordinary central station instrument whose capsule is exactly like those employed in the previous experiments, was used. This was suspended on spiral spring leading wires so that it was free from jar. The sound was produced by an organ pipe (256 vibrations) near the mouth-piece of the transmitter. The phenomena exhibited by this instrument differ very little from those already described with a quiet transmitter, except that the changes in resistance are much less as would be expected. One interesting result was noted which shows again the conservative action of the transmitter. When the sound is turned on, the resistance of the transmitter is increased, due no doubt to the loosening effect of the vibration, but the resistance begins to decrease immediately. If the lip of the pipe is covered to stop the sound, but to leave other conditions unchanged, the resistance falls immediately but presently starts to rise again.

The results of the foregoing experiments indicate that the theory of the action of the transmitter is not complete and that more than area of contact must be taken into account to explain the changes in resistance. The action of the gas is certainly of importance. A further study of the effect of various conditions discussed above on the wave form has been begun and the results will be published in a future paper.

NOTES ON ELECTRODE AND DIFFUSION POTENTIALS.

By G. W. Moffitt.

IN a recent paper[1] the writer has shown that the differences of potential between liquid surfaces and the air above them may be considerably greater than had usually been supposed. In some cases the value of this contact potential difference was changed as much as three tenths of a volt by slightly contaminating the surface of the liquid. It was also found that the value of this contact potential difference for clean fresh liquid surfaces is a steady value,—at least within a few thousandths of a volt,—and it is probable that the small variations in the observed values are due to the difficulties entering into the experiment.

It seems quite reasonable to assume then that there exists at the clean bounding surface of a liquid and air a definite difference of potential. The value of this potential in certain cases may be zero.

J. J. Thomson's work[2] on the electricity of drops points to the same conclusion from entirely different experimental evidence, as does some recent work by McTaggart.[3] Thomson found that certain solutio ıs—zinc chloride in water for example—in contact with air seem to show no electrification after the concentration has reached a certain value. McTaggart observed the motion of small air bubbles through liquids in which an electrostatic field was maintained. The bubbles were held in the axis of a horizontal glass tube filled with the liquid by the rapid rotation of the tube on its axis. The bubbles were free to move with or against the field which was parallel to the axis of the tube. He points out that the electrification set free by a falling drop is less than the charge as computed from the surface density and the area of the drop surface, and considers this last charge as the one effective in static, cataphoresis experiments. This means that only a part of the charge on a drop is set free by being broken up in air or by striking an obstacle. This would be expected. We would expect, however, that a drop neutral in the static condition would be neutral also when falling or when striking an obstacle. For the purposes of the present paper we may neglect any possible effects due to differences of concentration in the

[1] Phys. Rev., N. S., Vol. II., No. 2, Aug., 1913.

[2] Phil. Mag., Ser. V., Vol. 37, p. 341, 1894.

[3] Phil. Mag., Ser. VI., Vol. 27, p. 297, 1914.

surface film for results referred to later show that the neutral condition of the drop prevails throughout great variation of concentration. These views are supported by the few instances where data by the two methods can be compared. It may also be pointed out that in the cataphoresis experiments the liquid surface is sharply concave while with splashing drops it is either irregular or sharply convex. In view of these facts it seems reasonable to assume that conditions of electrical neutrality are the same for drops as for a clean level surface of the same liquid, and that solutions may be selected by the falling drop method whose air-liquid potential differences are negligibly small.

In the writer's work mentioned above values of the diffusion potential plus the difference of the two air-liquid potential differences were given for various solutions. If the solutions used had been those found by Thomson to exhibit no electrification in air we should have had values of the diffusion potentials for those particular cases. We have then a method of measuring potential differences between solutions in certain cases which is independent of theoretical assumptions. For instance, the diffusion potentials of zinc chloride solutions may be measured for concentrations greater than those for which the solution pressure theory seems to hold,—as determined by measurement of the electromotive force of concentration cells. It is by no means evident that an electrode potential for an electrode in an aqueous solution of an electrode salt can be computed in many cases, and diffusion potentials determined in this way seem likely to be in error. Especially is this true for the more concentrated solutions. In the case where the dissolved substance does not contain the element of which the electrode is composed we are still more uncertain. It seems therefore, that a direct method, tedious and inaccurate as it may be, would lead to results worth while.

On looking over Thomson's data on the electrification due to the splashing of drops no results were found for the solutions used by the writer in the work referred to above. It was decided to set up an apparatus similar in principle to that used by Thomson, and study the air-liquid surface potential differences for these solutions. A sensitive Dolazalek electrometer was used to detect the presence of the charges. One pair of quadrants was earthed, and the other was connected by means of a small copper wire to the solution in an insulated glass funnel from which the drops fell on a brass plate elevated from the bottom of a brass vessel in which the solution accumulated after splashing. This brass vessel was also insulated from the earth and connected to the insulated quadrants. Instead of using a fan to remove the charged air from the vicinity of the splashing drops a piece of brass tubing, flattened at one

end somewhat like a fishtail burner, was placed in a horizontal position on a line just above the plate on which the drops fell, and a few inches from the side of the brass vessel. This tube was connected to the compressed air supply and a gentle, steady stream of air kept passing over the vessel. The apparatus was frequently tested during the experiments for leakage and spurious charging effects by placing everything in position and observing the action of the electrometer when the solution was not dripping from the funnel. At times a slight positive charging was noted and wherever it appeared correction has been made for it in the results given below.

Distilled water was tried and a positive charge accumulated quite rapidly. A normal solution of sodium chloride was next tried and no charging resulted. Another portion of the solution was watered up to 0.5 normal. This produced no charging effect. Nor did a 0.1 normal solution prepared in the same way. A little distilled water was then run through the funnel to clean it and then the positive charging due to water was again observed. This is an example of the procedure in all cases distilled water being used before and after each series of solutions. In a similar manner solutions of sodium bromide, sodium sulphate, copper sulphate, and copper chloride were tried. All these were neutral in air at concentrations ranging from normal to less than tenth normal. Since the object of the experiment was to determine whether these solutions were neutral to air throughout this range of concentration no pains were taken to accurately measure the concentration.

These results show that the values published by the writer in PHYSICAL REVIEW, page 106, 1913, are, except in the case of zero concentration, the sum of the constant plate surface potential plus the liquid-metal potential difference in each case, and that the results on page 107 are the values of the diffusion potential differences for the solutions named.

Further, the effect of the anion on an electrode potential has been the subject of considerable discussion. It is generally looked upon as having little to do with the value of an electrode potential in the case where the cation is the same as the electrode. The variations in the two $ML + K$ curves for copper sulphate are probably due to uncontrolled factors. The two curves for sodium chloride also show some irregularities. The curve for sodium bromide lies close to the chloride curves, indicating that there is not much difference in the effects of these two anions on the electrode potential. The sodium sulphate curve, however, is removed from the other sodium curves, indicating that the sulphate ion has a different effect on the electrode potential than the halogen ions have. In these examples the cation is not the same as the electrode.

Why the anion should not affect the electrode potential is not clear. It seems more reasonable in the light of such cases as that just mentioned, to assume that in general the anion probably does exert some influence and that for the dilute solutions employed in concentration cells the effect at one electrode may be very nearly balanced by the oppositely directed effect at the other.

STATE UNIVERSITY OF IOWA,
September, 1914.

THE LEDUC EFFECT IN SOME METALS AND ALLOYS.

By Alpheus W. Smith and Alva W. Smith.

IF a metal plate having a longitudinal flow of heat in it is placed in a magnetic field which is perpendicular to the plane of the plate, a transverse difference of temperature is observed. This effect may be described as a rotation of the isothermal by the magnetic field and is known as the Leduc effect. This transverse difference of temperature $\Delta\theta$ will be determined by the width of the plate w, the longitudinal temperature gradient $\partial T/\partial x$, the magnetic field H and the nature of the plate. The coefficent of the Leduc effect ${}_hT_h$ is given by the equation,

$$\Delta\theta = {}_hT_h\, wH \cdot \frac{\partial T}{\partial x}.$$

According to the notation of Hall and Campbell[1] which is being followed, the T calls attention to the fact that the observed effect is at right angles to the longitudinal flow of heat; the subscript h preceding T indicates that the longitudinal flow is thermal and the other subscript h indicates that the transverse effect is thermal. Fig. 1 shows the accepted convention as to the sign of the coefficient. The rectangle represents the metal plate to be investigated; the arrows at either end of the plate, the direction of the longitudinal heat current and the arrows on the circle, the direction of the magnetizing current. If the rotation of the isothermal is in the direction in which the magnetizing current flows, the coefficient ${}_hT_h$ is said to be positive.

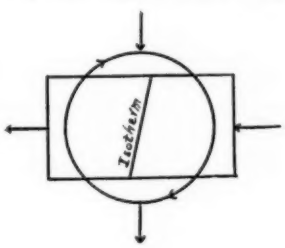

Fig. 1.

The plates used for this investigation were about 3 cm. long, 1.7 cm. wide and 1 or 2 mm. thick. In Fig. 2 is shown a plate with the copper-advance thermal couples attached for measuring the longitudinal temperature gradient and the transverse change of temperature. The longitudinal thermal couples C and D were soldered to the surface of the plate; the transverse ones A and B were imbedded in the edges of the plate and held in position by as small amount of solder as possible. The thermal junctions which were not soldered to the plate were in each case

[1] Proc. Am. Acad. of Arts and Sci., 46, p. 625 (1911).

immersed in a constant temperature-bath which was kept at room temperature. The thermoelectric heights of these thermal couples were determined over the range of temperature used in these experiments. The plate was soldered to copper projections from two rigidly connected copper tubes. Through one of these tubes flowed water at room temperature; through the other, steam. The plate was enclosed in a thin box of hard rubber or black fibre and the box was filled with magnesia oxide. The plate was then rigidly mounted between the poles of the electromagnet.

The couples with which the longitudinal temperature gradient was determined were used in the usual manner with a slide-wire potentiometer. The transverse temperature difference set up by the magnetic action was determined by connecting the thermal couples which were connected to the opposite sides of the plate, differentially to the coils of a Broca galvanometer. Since these couples could not be located exactly on the same isothermal, the galvanometer would in general show a deflection before the magnetic field was established. In order to compensate for any such inequality of thermoelectromotive forces tending to give a deflection of the galvanometer a slide-wire potentiometer was arranged in series with one of the coils of the galvanometer so that any electromotive force necessary to bring the galvanometer needle to its zero position could be introduced. The magnet was placed about 30 feet from the galvanometer and so oriented that the excitation of magnet produced less than a millimeter deflection in the galvanometer on open circuit. With the plate in position between the poles of the magnet a steady stream of water at room temperature was passed through one of the copper tubes and steam, through the other. When the flow of heat had become steady, the galvanometer circuit was closed and the slider on the potentiometer was adjusted so that the galvanometer showed no deflection. With the galvanometer circuit open the magnetic field was established. As soon as conditions of equilibrium had been reached, the deflection of the galvanometer corresponding to the change of temperature at the edges of the plate was noted. The observations were repeated with the magnetic field reversed. The mean of these observations was taken as the deflection corresponding to the change of

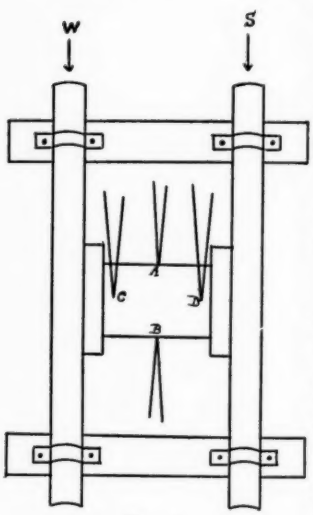

Fig. 2.

temperature due to the magnetic action. Three or more such sets of observations were taken for each magnetic field. From the average of these deflections, the sensibility of the galvanometer and the thermo-electric height of the thermal couple the transverse change of temperature between the edges of the plate was calculated. The mean of the temperatures of the ends of the plate was taken as the temperature of the middle of the plate and, therefore, the temperature at which the Leduc coefficient was determined. The deflection increased for nearly a minute after the excitation of the magnet. The readings were taken when a constant deflection had been reached. The sensibility of the galvanometer which for a fixed scale distance of about 200 cm. amounted to about 5×10^{-7} volts per cm. was taken for each series of observations.

In Table I. are given the results for nickel, nichrome, electrolytic

TABLE I.

Nichrome, $T = 56.9°$.		Nickel, $T = 61°$.	
H	$\frac{\Delta\theta}{w} \div \frac{\partial T}{\partial x}$.	H	$\frac{\Delta\theta}{w} \div \frac{\partial T}{\partial x}$.
2,130	16.7×10^{-4}	2,340	34.9×10^{-4}
4,320	33.6	4,300	58.6
6,550	39.0	6,320	66.4
7,970	41.9	8,500	67.3
9,120	41.9	10,880	68.9
9,820	41.9		
10,800	41.9		

Electrolytic Iron, $T = 56.9°$.		Cobalt, $T = 53.7°$.	
H	$\frac{\Delta\theta}{w} \div \frac{\partial T}{\partial x}$.	H	$\frac{\Delta\theta}{w} \div \frac{\partial T}{\partial x}$.
4,284	18.1×10^{-4}	4,200	29.2×10^{-4}
6,650	27.5	6,600	44.3
8,200	34.4	8,000	52.4
11,900	46.7	11,800	75.6
15,800	62.9	15,800	86.4
18,900	74.6	18,900	86.5
21,400	79.0	21,400	86.4
23,100	81.2		

iron and cobalt. The nickel and cobalt were obtained from Kahlbaum. The electrolytic iron was kindly furnished by Professor Burgess, of the University of Wisconsin. It has been shown that this iron is very free from impurities. In Table I. T is the temperature at the middle of

the plate where the effect was observed; H is the magnetic field in gausses; $(\Delta\theta/w) \div (\partial T/\partial x)$ gives the transverse change of temperature in degrees Centigrade for a plate one centimeter wide with a longitudinal temperature gradient of one degree Centigrade per centimeter in it. These results are also shown graphically in Fig. 3, where field strengths in gausses have been plotted as abscissæ and $(\Delta\theta/w) \div (\partial T/\partial x)$ as ordinates. It will be observed that the Leduc effect in nickel is opposite to that in

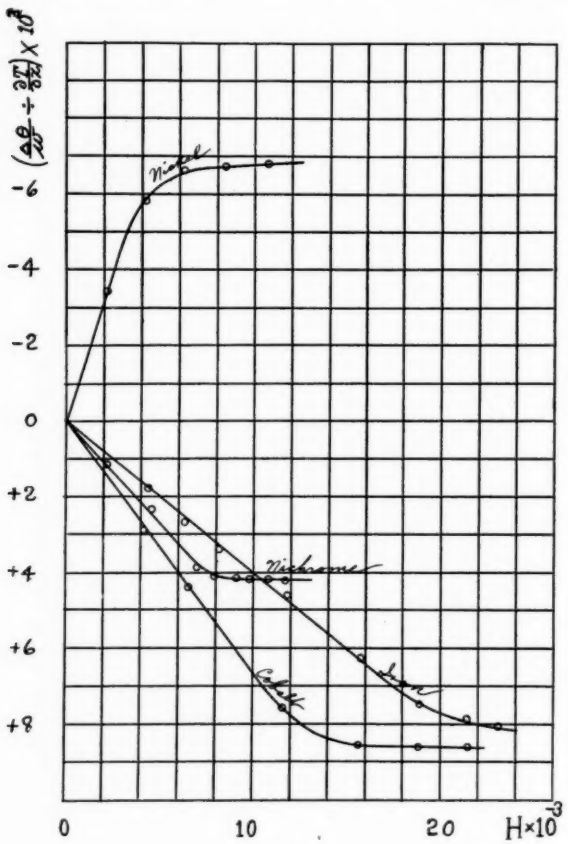

Fig. 3.

iron, cobalt and nichrome. For lower magnetic fields the effect is nearly proportional to the intensity of the magnetic field. For sufficiently high magnetic fields the difference of temperature set up by the magnetic action approaches a constant value. The curves showing the dependence of the Leduc effect on the magnetic field are exactly like those showing the dependence of the Hall effect and the Nernst effect on the magnetic field. In each of these three cases the effect is proportional to the

intensity of magnetization in the plate and not to the magnetic field. The observed effect, therefore, reaches a maximum value when the intensity of magnetization has reached its greatest value.

In Table II. are recorded the Leduc coefficients ${}_AT_h$ for a number of metals studied together with the field strength and the temperature at which the observations were made. The sign prefixed to the coefficient indicates the direction of the effect according to the convention explained earlier in this paper. The values for iron, zinc and antimony are in good agreement with the corresponding values given by Zahn[1] but the values for nickel and cobalt do not agree well with his values. For the sake of

TABLE II.

Metal.	H	${}_AT_h \times 10^8$	Temp. °C.
Nickel	10,880	− 61.5(20)	61.0°
Cobalt	11,800	+ 64.0(13)	53.7°
Nichrome	10,800	+ 38.8	59.3°
Electrolytic iron	11,900	+ 39.2(39)	56.9°
Molybdenum	12,300	− 17.5	57.5°
Tungsten	12,200	+ 15	58.6°
Cadmium	12,200	+ 11	60.5°
Zinc	10,900	+ 12.4(12.9)	58.5°
Antimony	11.000	+262.0(200)	56.7°

comparison Zahn's values have been inserted in brackets. For a field of 6,290 gauss Zahn gives for another specimen of nickel the value, -55×10^8. For iron Hall and Campbell found ${}_AT_h = +632 \times 10^9$ at 60° C. The lack of agreement between these observed values of ${}_AT_h$ must be attributed for the most part to the impurities in the metals and to their previous treatment.

The Leduc effect in two series of alloys—bismuth-antimony and antimony-zinc—has been studied. In the bismuth-antimony series of alloys the dependence of the effect on the intensity of the magnetic field was investigated for each of the plates. The results of these observations have been represented in Fig. 4. In this figure the transverse difference of temperature for a plate one centimeter wide with a temperature gradient of one degree Centigrade per centimeter has been plotted as ordinates and the magnetic field in gausses as abscissæ. It is seen from this figure that the transverse difference of temperature in bismuth and the alloys which contain a large percentage of bismuth increases less rapidly than the magnetic field. On the other hand in antimony and the alloys which contain a large percentage of antimony there is a linear

[1] Ann. der Phys., 14, p. 886 (1904).

relation between the magnetic field and the transverse difference of temperature. The sign of the effect in antimony is opposite to that in bismuth. To show the dependence of the Leduc coefficient on the composi-

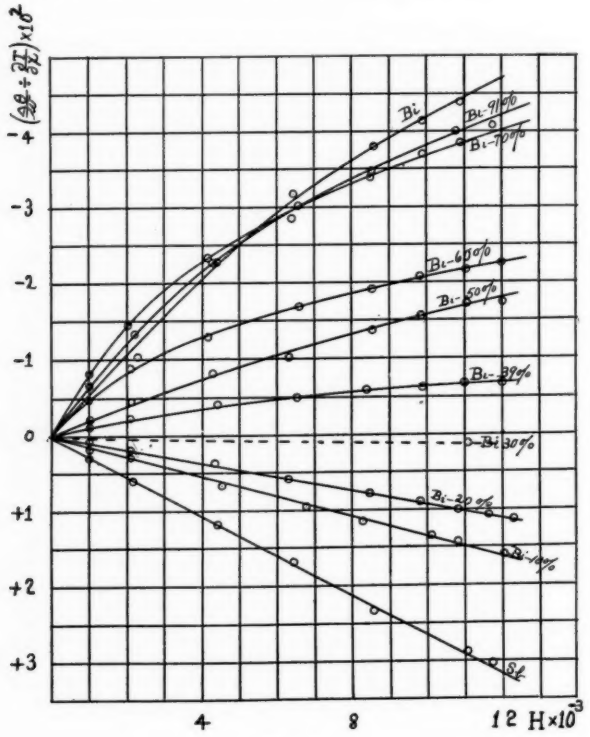

Fig. 4.

tion of the alloy Fig. 5 has been plotted with the Leduc coefficients as ordinates and the percentages by weight of antimony as abscissæ. The Leduc coefficients plotted in Fig. 5 were determined at a temperature of about 52° C. and with a magnetic field of about 11,000 C.G.S. units. The addition of antimony to the bismuth decreases the Leduc coefficient. When the alloy contains somewhat less than 70 per cent. of antimony the direction of the effect is reversed and for alloys containing more than this amount of antimony the direction of the effect is positive. The data from which this curve was plotted have been given in Table III.

In the antimony-zinc series the Leduc coefficient for each alloy was determined only for one intensity of the magnetic field which was in the neighborhood of 11,000 C.G.S. units. The temperature on the isothermal midway between the ends of the plate was about 57° C. This is, therefore, the temperature at which the coefficients were determined. Table

TABLE III.

Composition.		$\Delta T_h \times 10^5$	H
Per Cent. Sb.	Per Cent. Bi.		
0	100	−405	10,900
9	91	−375	10,800
30	70	−354	11,000
40	60	−195	11,000
50	50	−154	11,000
61	39	− 60	12,000
70	30	+ 9.5	11,100
80	20	+ 95	10,800
90	10	+132	12,060
100	0	+262	11,000

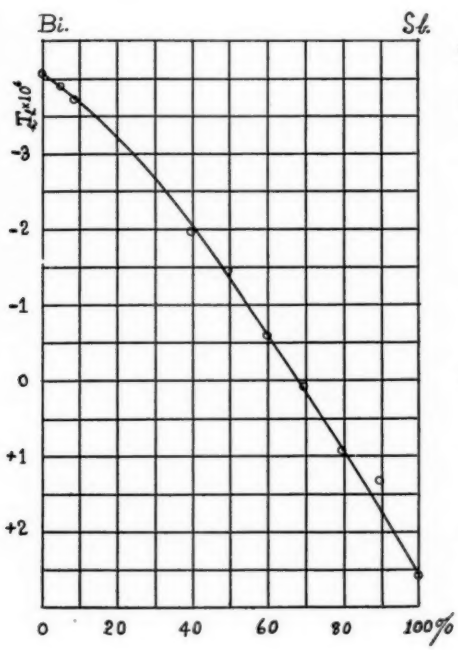

Fig. 5.

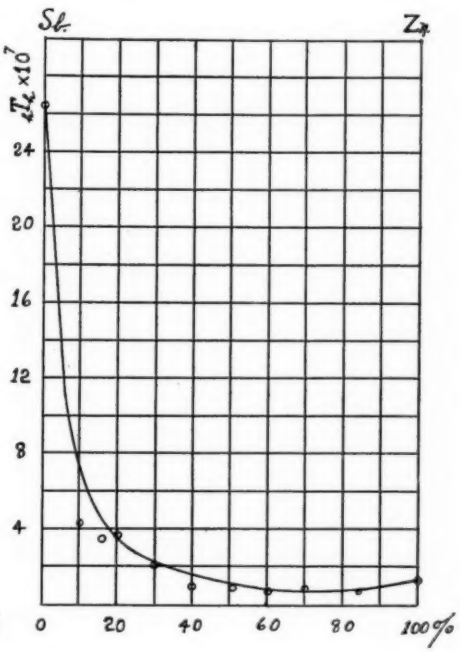

Fig. 6.

IV. gives the data on this series of alloys. These data have also been plotted in Fig. 6. The ordinates are the Leduc coefficients and the abscissæ the percentages by weight of zinc. The addition of a small percentage of zinc causes a very rapid decrease in the Leduc effect, so that when the alloy contains about 20 per cent. of zinc the Leduc coefficient is slightly more than one tenth as large as that in pure antimony. With the further addition of zinc the coefficient seems to pass through a not very well defined minimum.

TABLE IV.

Composition.		$_hT_h$	H	Temp. °C.
Per Cent. Sb.	Per Cent. Zn.			
100	0	+262	11,000	56.7°
90	10	42.7	10,900	56.5°
84	16	32.0	10,900	57.2°
80	20	27.5	10,900	57.1°
70	30	20.9	10,900	57.5°
60	40	9.08	10,900	57.2°
50	50	8.50	10,900	55.7°
40	60	6.77	10,900	57.2°
30	70	8.40	10,900	55.3°
16	84	6.60	10,900	61.8°
0	100	12.4	10,900	58.5°

SUMMARY.

1. In the magnetic metals nickel, nichrome, iron and cobalt, the transverse difference of temperature set up by the magnetic action in the case of the Leduc effect is proportional to the intensity of magnetization in the plate and not to the intensity of the magnetic field. This difference of temperature, therefore, reaches its maximum value when the intensity of magnetization has become a maximum. The relation of this effect to the magnetic field which produces it is the same as the relation of the Hall effect and the Nernst effect to the magnetic field. In antimony the Leduc coefficient is independent of the intensity of the magnetic field.

2. The Leduc coefficient has been determined in tungsten, molybdenum, cadmium, a series of alloys of antimony and bismuth and a series of alloys of antimony and zinc.

3. The addition of antimony to bismuth decrease the Leduc coefficient but less rapidly than is to be expected from the additive law. The addition of zinc to antimony causes a very rapid decrease in the Leduc coefficient. An alloy containing 10 per cent. of zinc and 90 per cent. of antimony has Leduc effect only about one sixth of that in pure antimony. With the further increase in the amount of zinc the coefficient decreases to a not very well defined minimum from which it rises to the value in zinc.

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PHOTO-ACTIVE CELLS WITH FLUORESCENT ELECTROLYTES.

BY GEO. E. THOMPSON.

INTRODUCTION.

THE efforts of previous experimenters to prove a dependence of the photo-electric current on fluorescence, in the case where two metal electrodes immersed in certain fluorescent solutions are unequally illuminated, have not led to definite results. Minchin[1] and Hodge[2] suspected such a relation but Goldmann[3] thought the relation unlikely.

The present work was begun with the idea of securing any possible additional facts which may have a bearing on this subject. Several related facts have appeared during the progress of the work and these are also included in this paper.

OUTLINE OF EXPERIMENTAL WORK.

Preliminary experiments were performed in order to determine what materials and solvents give the largest effect and are, therefore, most suitable for further study.

Several different metals were used as electrodes.

The fluorescence of fluorescein was increased by dilution and by addition of caustic potash and the change of current on illumination sought for.

The variation of current with wave-length of exciting light was measured in several different substances and with two types of cell.

APPARATUS.

Two types of cell were used; a "Pt foil cell" and a "Ag film cell." The "Pt foil cell" was a glass box 6 cm. in depth, 1 cm. from front to back, and 4 cm. wide. Two thin strips of platinum foil about .3 cm. wide, reaching nearly to the bottom of the cell and leaving enough foil outside for making the connections to galvanometer leads, were placed about .3 cm. apart. These were held against the front wall of the cell by a piece of hard rubber and a brass spring which pressed against the

[1] Minchin, Phil. Mag., Vol. 31, pp. 207–238, 1891.

[2] Hodge, PHYS. REV., Vol. 28, p. 25, 1909.

[3] Goldmann, Ann. d. Phys., Vol. 27, p. 449, 1908.

back wall. A paraffin stopper was used to prevent evaporation. This type of cell allowed a thin film of liquid to creep in between the electrodes and the front wall of the cell. Fig. 1 shows two views of this cell.

The "Ag film cell" had the same dimensions as the "Pt foil cell." Contact was made with precipitated silver[1] electrodes by pressing a thin sheet of tin plate against each one by means of a spring clasp clothespin. In order for the light to reach the liquid in this type of cell it must first pass through the silver film. These electrodes transmitted from 20 to 30 per cent. of the incident light for all wave-lengths. On account of deterioration probably due to imperfect adhesion of the silver, this cell had to be reconstructed occasionally.

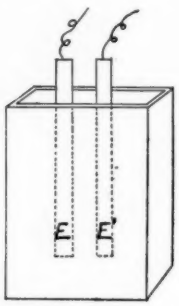

Fig. 1.

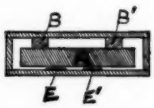

Fig. 1a.

When comparing the sensitiveness of different solutions without regard to the wave-length of the exciting light, a portion of the most active part of the spectrum from the spectrometer, described in the next paragraph, was used, or in cases where stronger illumination was required the arc light was focused upon the slit by means of a lens. A water cell was sometimes interposed to absorb heat rays but this was found to be unnecessary.

In studying the exciting power of various regions of the spectrum, a Nernst glower (110-volt A. C.) which furnished the exciting light was mounted in place of the slit of the spectrometer and an adjustable slit placed at the focus of the telescope lens permitted light of the wave-length desired to fall on one electrode of the sensitive cell. The slit width commonly used was .14 cm. The wave-length of the light used for excitation was varied by swinging the collimator arm with glower attached, the rest of the apparatus remaining fixed in position. The spectrometer arms were each about 60 cm. in length. A lead glass prism gave a visible spectrum about 7 cm. in length.

A Sullivan d'Arsonval galvanometer having a sensibility of 10^{-9}

[1] The Rochelle salts method. See Kohlrausch's Practischen Physik, p. 36.

ampere per mm. deflection with scale at 130 cm. distance, was used for measuring the current produced by the action of the light. Ordinarily about 20,000 ohms resistance were placed in circuit to diminish the current set up by the natural E.M.F. of the cell, which could not be completely eliminated.

Method of Observation.

The light was allowed to shine on one electrode of the cell until the maximum value of current was approximately attained. This value of current was used in comparing the photo-activity of solutions. In order to obtain data for various wave-lengths of exciting light, one of the electrodes was exposed successively to the various regions of the spectrum and readings of the current taken for each setting of the spectrometer, time enough being allowed at each setting for the current to reach approximately its maximum value for that color. About thirty minutes were usually sufficient for obtaining data for a complete curve; from three to five minutes per point.

Growth and Decay of Current.

Figs. 2 and 3 show the relation between time in minutes and current when one electrode of a cell is illuminated and also the decay of the current after the light is shut off. Galvanometer deflections, which are proportional to current, have been plotted. Each figure contains curves for growth and decay of current in a strong solution of rhodamin BX in

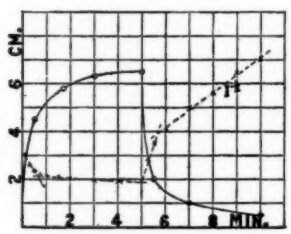

Fig. 2.

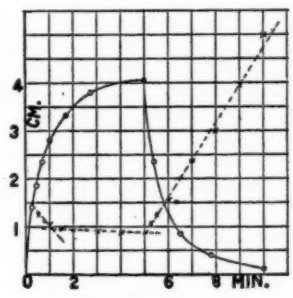

Fig. 3.

Rhodamin BX. Ordinates, galvanometer deflections in cm. Abscissæ, time in minutes.

absolute alcohol with the "Pt foil cell." For obtaining Fig. 2 a strip of electrode .14 cm. wide was exposed to the light; for Fig. 3, .08 cm. in width.

These curves are almost identical in form with those for growth and decay of intensity of phosphorescence in many substances that possess

long time phosphorescence. This similarity is made more evident by the fact that when the reciprocal of the square root of the current is plotted the broken line characteristic of phosphorescence is obtained.[1]

The same general explanation that applies to the growth and decay of phosphorescence is probably also applicable here, namely; that the total effect is the result of two effects, each of which follows a simple law, and which have different rates of growth and decay. In Fig. 3 one of these effects seems to be relatively less prominent as indicated by the more nearly linear character of the curve for $I^{-\frac{1}{2}}$.

The data obtained by Goldmann when plotted in the same way also indicate the same linear relation between $I^{-\frac{1}{2}}$ and time.

PRELIMINARY OBSERVATIONS.

In order to work with a comparatively weak source of light such as a Nernst glower where only a narrow portion of the spectrum is used it is desirable to have the most sensitive cell possible. It was found that the most fluorescent substances did not give the largest current under the action of light. Fluorescein, which was most fluorescent of all materials tried, gave a current too small to be measured when excited by the glower spectrum. Rhodamin BX, which possesses a fairly strong fluorescence, gave the largest effect of anything tried. Rhodamin R and rhodamin RRR and tetrabrom-fluorescein were mildly fluorescent and gave measurable effects. Fuchsin is weakly fluorescent but gave no current even when illuminated by the electric arc. The substances[2] tested were in all these cases in concentrated solution and used with the " Pt foil cell."

Among the solvents tried are absolute alcohol, water, grain alcohol, benzine, ether, alkaline and acidulated water and alcohol. Only alcohol dissolved sufficient quantities of the dye-stuffs for purposes of experiment so that the substances finally chosen for further experiment were rhodamin BX, rhodamin R, rhodamin RRR, tetra-brom-fluorescein and fluorescein; all in absolute alcohol.

Ordinarily the current flowed from the illuminated to the dark electrode outside the cell. The only exception noted was an alkaline water solution of fluorescein in which current could be excited only by the intense illumination of the arc. Due to the uncertainties involved in this particular case it is not quite safe to say that the current observed was a photo-electric current due to the fluorescein.

[1] Nichols and Merritt, PHYS. REV., Vol. 27, p. 370, 1908.

[2] The rhodamin BX, tetra-brom-fluorescein, fuchsin, and fluorescein used in these experiments were obtained from Merz & Co. of New York City. The rhodamin R and RRR were kindly furnished by Prof. Orndorff of the Chemistry Department of Cornell University.

The size of the current generated by the action of light was found to be dependent upon the material of the electrodes and upon their condition. Only a few of the metals used as electrodes produced a measurable effect. Of those tried, platinum foil, silver, gold, and oxidized copper were the only ones which gave a measurable current although the more obstinate ones were exposed to the direct illumination from the arc. Zinc, iron, polished copper, lead, tin and aluminum gave no effect. Platinum foil was best and the others followed in the order named.

PHOTO-ELECTRIC EFFECT AND FLUORESCENCE.

If the photo-electric current observed is directly connected with fluorescence we should expect that any increase in the fluorescence would be accompanied by an increase in the current. A dilute solution of fluorescein is more fluorescent than a concentrated solution, but repeated trials led to the conclusion that there is a loss of sensitiveness on dilution rather than an increase.[1]

The fluorescence of a fluorescein solution may be increased very markedly by adding a trace of caustic potash. Observation showed no change in the current when this was done. There is a chance here for error, however, unless all of the fluorescein is dissolved before the alkali is put in. The fluorescein is more easily dissolved after the addition of the alkali and an increase of photo-electric current which is really due to an increase of concentration may be wrongly attributed to the increase of fluorescence.

VARIATION WITH WAVE-LENGTH OF EXCITING LIGHT.

It has been pointed out by other observers that the maximum effect is produced in the region of maximum absorption, but definite data have not been given. Goldmann[2] found that the light included in the region of absorption produced practically the whole effect, but he did not disperse the light. Hodge,[3] and Rigollot,[4] state that the maximum effect was found on the red side of the absorption band just before entering the band. But as will be shown later this result would have been different had a correction been made for unequal energy distribution in the spectrum used for excitation.

[1] Since this work was done, a paper has been published by Mecklenberg and Valentine which states that the fluorescence of fluorescein is proportional to concentration if the absorption of the excited fluorescent light is corrected for. The above experiment is, therefore, based on a false but common assumption (Phys. Zeit., Vol. 15, p. 267).

[2] Goldmann, l. c., p. 476.

[3] Hodge, l. c.

[4] Rigollot, Journ. d. Phys. (3), Vol. 6, p. 520, 1897.

Fig. 4, Curve I., shows the variation of current with wave-length of exciting light, using the "Pt foil cell" with a fairly concentrated absolute alcohol solution of rhodamin BX; width of electrode illuminated, .08 cm. The ordinates of Curve *A* are proportional to the coefficients of absorp-

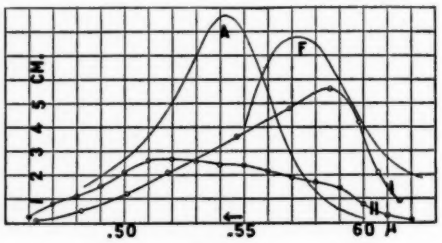

Fig. 4.

Rhodamin BX; "Pt foil cell." Ordinates of curve *A* are proportional to coefficients of absorption. Curve *F*, fluorescence; I., observed photo-electric current; II., corrected curve.

tion in a dilute alcohol solution. The general shape of the Curve *A* is the same as for a concentrated solution.[1] The fluorescence band for a dilute solution is represented approximately by Curve *F*.

Fig. 5 shows results obtained under similar conditions except that the

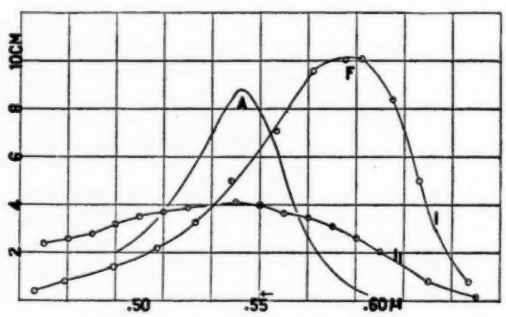

Fig. 5.

Rhodamin BX. *A*; absorption; I., photo-electric current; II., corrected curve. "Pt foil cell."

width of slit was .14 cm. On account of the larger current obtained, this curve is probably the most accurate of any that will be shown.

The results of Fig. 6 were obtained with the "Ag film cell" under similar conditions.

Fig. 7 contains curves for tetra-brom-fluorescein with the "Pt foil cell"; slit width, .14 cm.; absolute alcohol solution.

Fig. 8 shows two curves for rhodamin RRR using the "Pt foil cell";

[1] Nichols and Merritt, PHYS. REV., Vol. 31, p. 376, 1910.

absolute alcohol solution. They were both obtained with the same solution but with different areas of the electrodes exposed in each case; .08 cm. for the lower curve and .14 cm. for the upper.

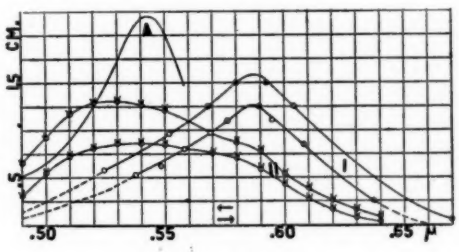

Fig. 6.

Rhodamin BX. Cell No. 2. I., observed curve; II., corrected curve. "Ag film cell."

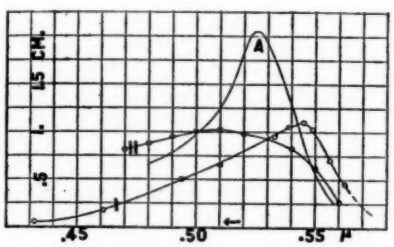

Fig. 7.

Tetra-brom-fluorescein. "Pt foil cell."

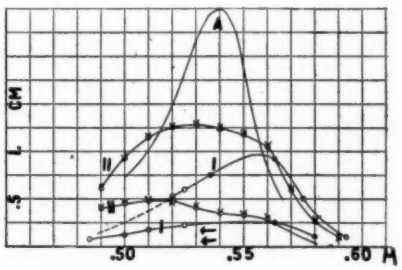

Fig. 8.

Rhodamin RRR. "Pt foil cell."

CORRECTIONS TO BE MADE.

The manner in which the photo-electric current depends upon the wave-length of the exciting light is more clearly brought out by correcting for unequal dispersion and unequal energy distribution throughout the spectrum of the glower. The dispersion for a particular wave-length was taken as an arbitrary unit with which the dispersion in other parts of the spectrum could be compared. Then for any wave-length the ratio of the dispersion to this arbitrary unit becomes the correction factor by which each corresponding ordinate of the observed curve must be multiplied in order to correct for unequal dispersion. Column 3 of Table I. gives values of these factors for various wave-lengths.

The intensity of the spectrum from the glower was then compared, wave-length by wave-length, with that of an acetylene flame by means of a spectro-photometer. Six sets of readings were taken throughout the spectrum and the average values used in computing the ordinates of the energy curve of the glower. Column 2 of the table gives the

results of this comparison. The curve given by Coblentz[1] for the energy distribution of the acetylene flame afforded a basis for the computation of energy distribution of the glower from the spectro-photometric comparison. The ordinates of the acetylene energy curve were multiplied by the numbers in column 2 in order to get the energy curve of the glower. The energy of some particular wave-length was taken as the arbitrary unit and correction factors for other wave-lengths found by comparing the ordinates of the glower curve. For example, the correction factor for the wave-length whose energy is one half the arbitrary unit is 2. Column 4 contains these correction factors.

TABLE I.

DATA FOR FIG. 4.

1	2	3	4	5	6	7
Wave-length.	Ratio of Glower to Acetylene.	Correction Factors for Dispersion.	Correction Factors for Energy Distribution.	Product.	Ordinates of Observed Curve.	Ordinates of Corrected Curve.
.450		1.05	5.08	5.34	0.00	0.00
.460		.92	4.40	4.04	.07	.28
.470	.89	.90	3.66	3.29	.25	.80
.480	.94	.80	3.14	2.51	.45	1.13
.490	.89	.75	2.85	2.14	.75	1.60
.500	.89	.75	2.54	1.85	1.15	2.12
.510	.91	.71	2.20	1.56	1.65	2.57
.520	.95	.70	1.78	1.25	2.20	2.75
.530	1.00	.64	1.53	.98	2.70	2.64
.540	1.04	.60	1.32	.79	3.20	2.53
.550	1.07	.55	1.16	.64	3.80	2.43
.560	1.04	.46	1.06	.49	4.30	2.16
.570	1.01	.38	1.00	.38	4.90	1.87
.580	1.01	.35	.91	.32	5.40	1.73
.590	1.02	.33	.82	.27	5.50	1.48
.600	1.04	.32	.74	.24	3.50	.84
.610	1.08	.30	.66	.20	1.50	.30
.620	1.13	.30	.57	.17	.50	.08
.630	1.17	.30	.51	.15	.10	.02
.640	1.20	.30	.46	.14	.00	.00

The product of the factors in columns 3 and 4 (column 5) gives the number by which each ordinate of Curve I. must be multiplied. The resulting curve represents, therefore, the current which would be produced by a normal spectrum of uniform energy distribution. Column 6 gives the ordinates of the observed curve and 7 those of the corrected curve of Fig. 4.

[1] W. W. Coblentz, Bull. Bur. of Stds., Vol. 7, p. 259, 1910.

SOURCES OF ERROR.

It has been recognized that the use of the galvanometer as a measuring instrument permits the polarization of the cell and may influence the results. But since Goldmann[1] has shown that the effect is only slightly diminished by polarization and not changed in character, it seems that results obtained in this way are not invalidated. Attempts were made to avoid this by using an electrometer but a quadrant electrometer (.001 volt sensibility) did not prove sensitive enough to measure the E.M.F. developed by the glower spectrum.

The spectrum had some overlapping of colors on account of the width of the source (about .5 mm.) and all colors were not accurately focused. The focus was accurate in the yellowish green. This impurity of the spectrum would not lead to any serious error.

The fluctuations of voltage on the glower were sometimes considerable but caused no serious disturbance because of the lag of the photo-electric current behind changes in intensity of the exciting light (see Fig. 2). The tendency is, therefore, for the effect to assume a value which corresponds to the average illumination.

The sensitiveness of the cell diminished slightly with each succeeding illumination but recovered somewhat when let stand in the dark. Finally the solution had to be renewed on account of permanent loss of sensitiveness.

It was more difficult to secure data with the "Ag film cell" on account of disturbances due to slight jarring, etc. The two curves shown were the best ones observed. These show an extrapolation in the blue, but several independent observations in this region prove this to be the correct form for the curves. On account of the disturbances, observations had to be made more hurriedly with this cell; hence, the necessity for extrapolation. When the observations were made it was not realized that this was to be the important part of the curve or the extrapolation could have been avoided in this region.

The displacement of the current maximum from the absorption band toward the blue may be due in part to the fact that in those cases the observations were begun in the red. If sufficient time were not given for the current to diminish to its normal value for each color, the values to the left of the maximum on the observed curve would be too large and might shift the maximum of the corrected curve. Sufficient data is not at hand to make this conclusion certain. There is also considerable difficulty in reproducing results.

The arrows at the bottom of the figures indicate the manner in which

[1] Goldmann, l. c., p. 500.

the readings were made; *e. g.*, an arrow pointing toward the blue means that readings were begun in the red and progressed toward the blue.

With the "Pt foil cell" we might expect the maximum to be somewhat diminished by the absorption of the layer through which the light must pass before it strikes the electrode. There is no very noticeable difference, however, between the corrected curves for the two types of cell.

SUMMARY OF RESULTS.

The curves for the growth and decay of the photo-electric current are similar to those for the growth and decay of phosphorescence. If $I^{-\frac{1}{2}}$ be plotted, the characteristic broken line is obtained.

The magnitude of the photo-electric current depends on the metal used as electrodes. Of ten metals tried, only platinum, gold, silver and oxidized copper gave a measurable effect.

The position of the maximum effect does not depend upon the material of the electrodes but upon the material in solution.[1] The effect is not the photo-electric effect of the metal in the liquid.

The experimental results do not show any close connection between the photo-electric current and fluorescence. Two methods of increasing fluorescence did not increase the current. The region of excitation for the current extends further into the red than for fluorescence.

All of the curves show the maximum photo-electric current approximately in the region of maximum absorption.

CORNELL UNIVERSITY,
July, 1914.

[1] Rigollot has mentioned this. Journ. d. Phys. (3), Vol. 6, p. 520, 1897.

A COMPARATIVE STUDY OF THE LIGHT-SENSIBILITY OF SELENIUM AND STIBNITE AT 20° C. AND − 190° C.

BY D. S. ELLIOTT.

IT is a well-known fact that selenium experiences a decrease of resistance when exposed to light under the proper conditions, and several explanations for this fact have been offered. It was suggested by Pfund[1] that the conduction in selenium is electronic and that the increased conductivity may be accounted for on the assumption that the absorbed light sets electrons in resonance resulting in their expulsion outside the atoms. This would increase the number of electrons available for carrying the current and hence increase the conductivity.

Among the facts that can be marshalled in support of the electronic hypothesis, the most important are these:

1. As shown by Thomson in his "Conduction of Electricity Through Gases," the current through an ionized gas is proportional to the square root of the energy of the ionizing agent, provided the ionization has reached a steady state. The same law has been shown by Pfund[2] and Nicholson[3] to hold for selenium for unlimited exposures to radiation from $\lambda = 230\mu\mu$ to $\lambda = 900\mu\mu$ and for X-rays.

2. Another general property of electronic conduction is the absence of polarization. A number of investigators[4] have definitely established the fact that normal selenium cells show no polarization. This proves that the conduction is not electrolytic.

3. The retention of light-sensibility at the temperature of liquid air is also evidence for the electronic hypothesis. This property of selenium is clearly shown by the experiments of Pochettino,[5] Miss McDowell[6] and the author.

4. All light-sensitive substances show the "voltage effects"; *i. e.*, Ohm's law is not obeyed. Ries,[7] Adams[8] and Luterbacher[9] have shown

[1] Pfund, PHYS. REV., 28, 1909, p. 324.
[2] Pfund, PHYS. REV., XXXIV., No. 5, May, 1912.
[3] Nicholson, PHYS. REV., Vol. III., Jan., 1914.
[4] Ries, "Electrical Properties of Selenium," p. 53. Pfund, Phys. Zeit., 10, 340, 1909.
[5] Pochettino, Rend. R. Accad. dei Linc., Sec. 5, Vol. II., p. 286.
[6] McDowell, PHYS. REV., 31, p. 524, 1910.
[7] Ries, Phys. Zeit., 12, p. 480 and 552, 1911.
[8] Adams, Proc. Roy. Soc., 23, 1875.
[9] Luterbacher, Ann. d. Phys., 33, 1392, 1910.

that the specific resistance of selenium decreases with an increase of voltage, and also decreases as the current continues to pass through the cell.

Object of Investigation.—As the information on selenium at liquid air temperature was not as complete as might be desired, it seemed advisable to investigate this further. The particular object of the investigation, however, was to examine other light-sensitive substances and determine whether or not they showed behavior similar to selenium at 20° C. and − 190° C. Most of the observations have been confined to stibnite.

Cells.—In order to carry out this investigation, it was first necessary to prepare cells which would meet the extreme demands necessitated by this temperature variation. It soon became evident that selenium cells prepared in the usual way would not suffice, as it was found that after a cell had been subjected to the temperature of liquid air and was brought back to 20° C., its behavior was markedly different. After some experimenting, cells were constructed according to the following design which is due to Professor Pfund. This cell has proven so satisfactory that it seems well to describe it in some detail.

Selenium Cells.—Amorphous selenium was first cast into discs about 1.5 cm. in diameter and 1.5 mm. thick. They were sensitized in the usual way, being maintained at a temperature of 200° C. for six hours and then cooled rapidly to room temperature. The discs were then ground smooth on crocus cloth, after which silver tape electrodes were fastened on with celluloid. A film of gold was next deposited by cathode sputtering, and finally the gold was removed along a narrow line like a grid as shown in Fig. 1. Attention is called to the four shallow pools of

Fig. 1.

Fig. 2.

Fig. 3.

celluloid shown. Besides strengthening the construction these provide a smooth transition from the selenium to the upper surface of the silver tape. In this way fractures of the gold film were avoided. The time required for the deposition from the insertion of the cell to its removal did not exceed twenty minutes; but as a matter of fact, the selenium was covered with a protective layer of gold within six minutes. No

deleterious action due to mercury vapor could be detected. The cell was finally enclosed in a glass tube similar in design to Fig. 2. Bulb *B* was filled with calcium chloride and the constriction leading to the upper chamber loosely plugged with cotton. The cell "*c*" was fastened with sealing wax in this upper chamber, the end of which was closed by a glass plate. The vessel was also provided with a side tube for exhausting by means of an aspirator, a phosphorus pentoxide tube being inserted between cell and aspirator during the process.

Stibnite Cells.—Stibnite cells were made and mounted in essentially the same way as the selenium cells. Starting out with crystals of stibnite[1] (Sb_2S_3) and using the cleavage surfaces, in some cases gold was deposited over the whole surface and afterwards removed along a line by scratching; in other cases a protective layer of tin-foil about 0.5 mm. wide was placed along the middle of the surface before deposition. This tin foil was afterwards removed disclosing a strip of clean cleavage surface which could be exposed to the light. Fig. 3 is a picture of a stibnite cell.

Apparatus.—The arrangement of apparatus is shown in Fig. 4. The source of illumination was a Nernst lamp *L*; a spectrometer of the Wadsworth type broke up the radiation into quasi-monochromatic light focused in the plane of slit S_2; the light could then follow one of two paths depending upon whether the right-angle prism *P*, hinged at *H*, was raised or lowered. With the prism *P* swung out of the way, the light was focused by the lens L_2 on a sensitive thermal junction. This system, constructed according to his latest design,[2] together with a sensitive galvanometer, was built by Professor Pfund and kindly placed at my disposal. Its sensibility was such that a candle at a meter's distance gave a deflection of 30 mm. With the prism *P* down, the light was diverted downward upon cell "*c*" which was inserted in a Dewar flask. The amount of glass in the path of the beam over both paths was approximately the same, and it might be said at this point that in carrying out any set of experiments to determine the effect of temperature or anything

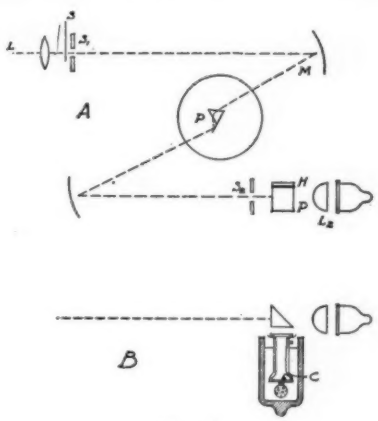

Fig. 4.

[1] The crystals of stibnite were generously furnished by Dr. W. W. Coblentz of the Bureau of Standards.

[2] Pfund, Phys. Zeit., XIII., 870, 1912.

else, that particular factor could be varied alone without disturbing the cell in any way. Results obtained are therefore strictly comparable.

In measuring increased conductivity the usual method was employed. Diagram 5 shows the arrangement. In some cases a counter E.M.F. was introduced at the galvanometer terminals to annul the "dark deflection," and when the increased conductivity was too large, a shunt R was introduced to cut down this deflection. In some cases both the counter E.M.F. and the shunt were unnecessary. Both this galvanometer (sensibility 1.5×10^{-8} amperes) and a device for exposing for the desired time, were placed in an adjoining room. In general, exposures of ten seconds were taken, and an interval of three or four minutes elapsed between readings.

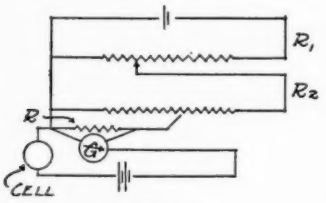

Fig. 5.

Sensibility Curve. Selenium 20° C.—In these observations, cells of the new design were used. Strictly speaking the sensibility of a cell is the ratio of the two quantities—the change in resistance per unit energy illumination, and the dark resistance. The quantity used in plotting these curves is proportional to this. The galvanometer deflection corresponding to a certain value of incident energy was first obtained. The deflection corresponding to a particular value of energy taken as unity could then be calculated from the relation $D = KE^{\beta}$ where D is the galvanometer deflection, K a constant, E the incident energy and β another constant. For unlimited exposures, Pfund and Nicholson have shown that $\beta = 0.5$, and this is the value used in applying the formula unless definitely stated otherwise. Attention is called to the fact that actual observations near the sensibility maximum were taken for energies which do not vary appreciably from the value of energy taken as standard. This was accomplished by adjusting the voltage on the Nernst lamp and the width of the slit S_1. In this way all possibility of vitiation of the results by the assumption of any law connecting galvanometer deflections and energy was obviated. Curve I. gives the sensibility curve for selenium cell D, temperature 23°.5 C., 120 volts.

Sensibility Curves of Selenium at − 190° C.—In taking these curves the Dewar flask was filled with liquid air and replaced about the cell. This adjustment could be effected without disturbing the rest of the apparatus. Sufficient care was taken to see that the flask remained well filled with liquid air. By means of a funnel arrangement, not shown in the drawing, the supply of liquid air could be replenished without withdrawing the flask, so that the cell remained undisturbed in liquid air

throughout the experiment. In all recorded experiments the cell was brought to this low temperature very gradually, and throughout the procedure the conductivity was observed to fall very rapidly until it

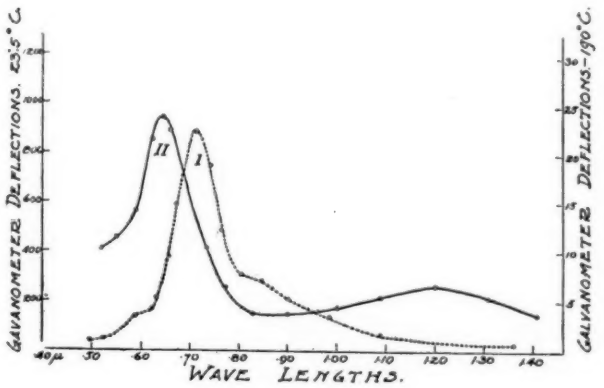

Fig. 6.

became barely perceptible. Observations of Pochettino[1] and Miss McDowell[2] also show that the resistance of selenium at liquid air temperature is enormously great.

In the early part of the work some experiments were carried out to determine whether or not the ratio of the increased conductivity to the original conductivity—$\Delta c/c$—was independent of the temperature for any one wave-length. Fig. 7 gives the arrangement of the apparatus for this part of the work. The circuit containing the cell c and a storage battery B was completed through S the secondary of a transformer; the primary coil P was connected to a sensitive galvanometer G. Exposures of 0.2 second were obtained by means of a pendulum also shown in the drawing, and a device was fixed to the pendulum so as to break the primary circuit slightly before the exposure of 0.2 second was completed. In some cases $\Delta c/c$ was independent of the temperature, in other cases this ratio increased with temperature, while in still other cases it decreased as the temperature was raised. In all cases, however, the results were of the same order of magnitude. A possible explanation based on a change of optical properties is suggested from a consideration of the change in sensibility curves for the two temperatures. The striking fact, however, is that the light becomes

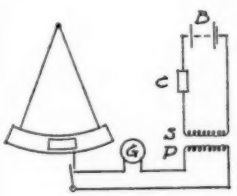

Fig. 7.

[1] Pochettino, Rend. R. Accad. dei Linc., Sec. 5, Vol. II., p. 286.

[2] McDowell, PHYS. REV., 31, p. 524, 1910.

effective at the temperature of liquid air just as rapidly as at ordinary temperatures, while the recovery for the lower temperature is very much slower.

A typical sensibility curve for selenium at − 190° C. for a ten-second exposure is shown in Curve II. In making all observations at liquid air temperature, the cell was afterwards brought back to room temperature to determine whether or not the first readings could be reproduced. This is the reason why early observations on cells of standard design were discarded as worthless. With the new design no difficulty was experienced.

Voltage effects were detected at liquid air temperature.

From a comparison of Curve I. and II. the following conclusions seem to stand out most pronounced: Lowering the temperature of selenium from 20° C. to − 190° C. causes

1. An extension of the range of sensibility from 0.9 μ to 2.0 μ approximately.
2. A shift of the sensibility maximum towards the region of shorter wave-lengths by about 600 A.U.

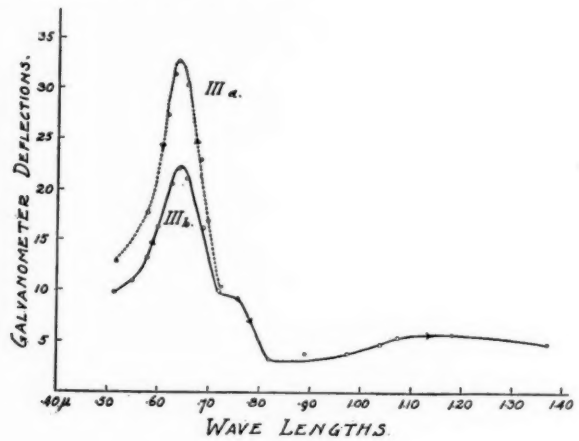

Fig. 8.

The position of the sensibility maximum is unaffected by the voltage effect and the direction of progression through the spectrum. This is shown by Curves III_a and III_b which refer to selenium at − 190° C. Curve III_b as indicated by the arrow is plotted from readings taken through the spectrum from shorter to longer wave-lengths, Curve III_a refers to the same cell, readings being taken in the reverse order. During the course of the readings the conductivity was observed to increase appreciably although the temperature must have remained constant. The position of the sensibility maximum, however, is unaffected.

Stibnite.—The light sensitive property of stibnite (Sb_2S_3) was discovered by Jaeger[1] in 1907, and Ries[2] showed later that this substance exhibits the same voltage effects as selenium. It was decided to investigate this substance further, using as the mode of attack the sensibility curves obtained under various conditions. The cells were mounted in the same way as the selenium cells previously described.

Law Connecting Energy and Deflection. Room Temperature.—In investigating this point a rotating sector was placed before the spectrometer slit S_1 (see Fig. 4). The disc was so constructed that by sliding the motor along a pair of ways, full, one half, or a quarter energy was allowed to fall on the slit, and the resulting galvanometer deflections could be obtained. The accompanying table is representative of this part of the work.

Exposure 10 sec. 110 volts. 21° C.

Wave-lengths.	D_1=Galv. Defl. Full Energy, Mm.	D_2=Galv. Defl. ½ Energy, Mm.	D_3=Galv. Defl. ¼ Energy, Mm.	β Calc. from D_1 and D_2.	β Calc. from D_1 and D_3.
0.642μ	9	6.2	4	0.54	0.58
.670	16	11	7.7	0.54	0.53
.685	27.5	19.3	13.7	0.51	0.53
.700	59	39	26.7	0.59	0.57
.740	137.5	95.1	66.7	0.53	0.52
.768	86.75	54.5	35.8	0.67	0.64
.800	39.5	23	15.1	0.78	0.69
.873	7	3	2	1.02	0.92

Exposures of ten seconds were made, and the relation $D = KE^{\beta}$ was assumed to hold between galvanometer deflection D and the energy E. Having two values of D as well as the ratio of the corresponding energies, the value of β is easily calculated. It will be observed from the foregoing table that the value of β for shorter wave-lengths is in general less than for the longer wave-lengths. This is similar to what we find in selenium. The obvious explanation is that a greater time is required for equilibrium for the longer wave-lengths. For the same reason the value of β for all wave-lengths is too large. For exposures sufficiently long enough to ensure equilibrium, it is safe to say that the square root law holds for stibnite. In other words, stibnite obeys the law $D = KE^{\beta}$ where D is the galvanometer deflection, K is a constant, E the energy and $\beta = 0.5$ approximately.

Sensibility Curve for Stibnite at Room Temperature.—Two specimen sensibility curves will be given in this connection. Both refer to the

[1] Jaeger, Proc. Roy. Acad. Sci. Amsterdam, 9, 808, 1907.

[2] Ries, Ann. d. Phys., 36, 1911, p. 1055.

same stibnite cell—cell "*A*," which had a scratched surface. The first observations were taken by exposing the cell until equilibrium was reached. Owing to the voltage effect in stibnite the galvanometer never came absolutely to rest, but equilibrium was considered to have been reached when the galvanometer moved less than 1 mm. per minute. After each reading the cell was allowed to "soak" back approximately to its original conductivity before the next reading was taken. Intervals between readings amounted in some cases to as much as thirty-five minutes. Curve IV. gives these results. Curve V. refers to the same

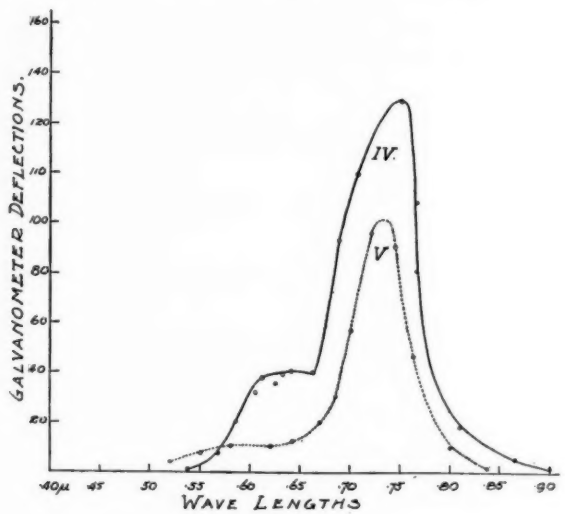

Fig. 9.

cell, readings being taken for exposures of ten seconds. All other conditions were practically the same. Comparing Curves IV. and V., we see that for unlimited exposures the sensibility maximum lies further in the red. An explanation of this fact is that while equilibrium is approximately reached for the shorter wave-lengths in ten seconds, such is not the case for the other end of the spectrum. The effect of longer exposures is therefore to increase the ordinates corresponding to longer wave-lengths, leaving the short wave-lengths practically unaffected. Consequently the maximum shifts towards the longer wave-lengths.

Voltage Effects.—As other investigators[1] have already observed, stibnite shows the voltage effects. The specific resistance decreases with the voltage; and for the same voltage, the resistance decreases with time. Like selenium, stibnite cells do not regain their original conductivity

[1] Ries, Ann. d. Phys., 36, 1655, 1911.

immediately but require time. Compared with selenium, however, this return is much more rapid.

Stibnite at the Temperature of Liquid Air.—Sensibility curves were obtained at this temperature, and the law connecting galvanometer deflections and energy investigated. A cursory examination seemed to indicate that at this temperature the square root law held for equilibrium exposures, but as it was proposed to use an exposure of ten seconds for the sensibility curves, the law connecting energy and deflections was investigated under these conditions. The data referring to this part of the work follows:

Stibnite Cell "*D*." Temperature − 190° C.
Voltage 120. Exposure 10 sec.

Wave-lengths.	D_1 = Galv. Defl. Full Energy. Mm.	D_2 = Galv. Defl. Half Energy, Mm.	β Calc. from D_1 and D_2.
0.577	13.65	8.3	0.71
0.616	17.25	10.14	0.74
0.735	21.6	12	0.85
0.813	30.9	17.97	0.78
		Mean value	0.77

Sensibility Curves of Stibnite at − 190° C.—A number of experiments were carried out on different cells of both the scratched and the unscratched variety. Curve VIII. is a typical curve. Although the value

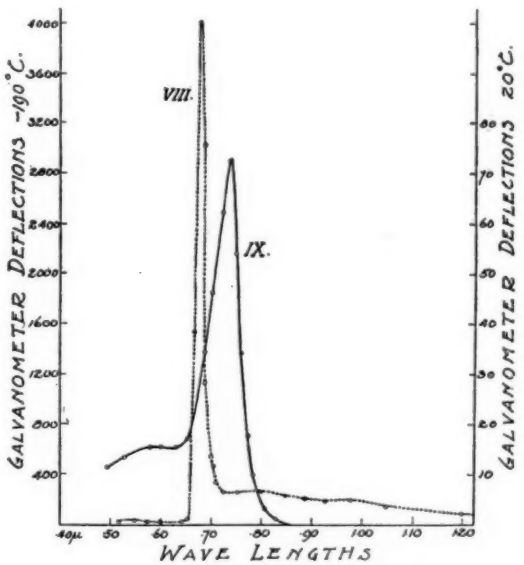

Fig. 10.

of β used in reducing the deflections to equal energies was 0.77, a calculation showed that there would be no sift of the position of the sensibility maximum for values of β ranging from 0.5 to 1.0. Curve IX. refers to the same cell at room temperature.

From a comparison of Curves VIII. and IX., these two conclusions stand out most prominently: Lowering the temperature of stibnite from 20° C. to − 190° C. causes:

1. Extension of the region of sensibility to 2 μ approximately.
2. Shift of the sensibility maximum towards the region of shorter wave-lengths by about 600 A.U.—approximately the same as for selenium.

Anomalous Stibnite Cells.—In addition to the general characteristics enumerated above, two cells—stibnite cell "*B*" and stibnite cell "*X*," exhibited some surprising properties. A preliminary test with an incandescent lamp indicated that these cells were quite normal, but with monochromatic light some unexpected properties were found. For certain regions of the spectrum these cells were photo-negative, while for longer wave-lengths they were photo-positive. The performance of stibnite cell "*B*" is given in the following table:

Stibnite Cell "*B*." Temperature 20°.5 C.
Voltage 20. Exposure 10 secs.

Wave-lengths.	E_1 = Energy Defl., Mm.	D_1 = Galv. Defl., Mm.	E_2 = Energy Defl., Mm.	D_2 = Galv. Defl., Mm.
0.5035μ	11.5	− 8	2.0	− 5
0.5302	20.5	−10	3.25	− 5
0.5602	40	− 7.5	7	− 7
0.5936	79	−10	14.5	− 7.4
0.634	160.5	− 5.2	31	− 5
0.657	219	0	47.5	0
0.695	229	+16	54	+ 9
0.724	234	+18	57.5	+10.5
0.767	198	+19.5	54.5	+ 4
0.806	185			

It seems well to mention that whenever the deflection was negative, an additional negative deflection was observed immediately after the light was turned off. Just what the explanation is, it is impossible to say, but it is certain that the effect is in the cell itself and is not due to external electrical influences. Glancing at the table, it is seen that no deflection is recorded for $\lambda = 0.657\ \mu$. The inference must not be drawn from this that the galvanometer remained entirely quiescent. As a matter of fact there was first a positive deflection of 1.5 mm., followed immediately by an equal negative deflection. No simple relation was found connecting energy and deflection. It is evident

that we are dealing here with the superposition of two effects. A superficial study shows that if the law $D = KE^{\beta}$ does apply, the values of β for the positive and the negative effects are entirely different.

At the temperature of liquid air this cell showed the maximum in the usual position. At this temperature the negative effect was entirely absent; the range of sensibility had been extended considerably, positive deflections being recorded from 0.48 μ to 2.5 μ. Returning to 20° C. the cell was found to be light negative again. The writer hopes to investigate photo-negative selenium cells prepared according to Brown's process,[1] to see whether or not this photo-negative property is fundamental in character.

Stibnite cell "X" when first prepared showed this photo-negative property even more strikingly than cell "B." Twenty-four hours later this had entirely disappeared and the cell though unsteady was normal in its behavior. The transient character of this photo-negative property as indicated by cell "X" is controverted by cell "B" fully described above. At the time of writing cell "B" which is a month old still retains its photo-negative characteristics. Further studies of these so-called anomalous cells are to be made with a more rapidly moving galvanometer.

THEORETICAL DISCUSSION.

More extended experimental data must be at hand before a theoretical discussion becomes profitable. It will be remembered however that Pfund[2] found the sensibility maximum of selenium to lie in the region of increasing transparency. Nicholson's[3] experiments also have a bearing in this connection. Koenigsberger[4] and Mueller[5] have found for stibnite an increasing transparency at the edge of the visible spectrum and Trowbridge[6] found a temperature shift of the transparency maximum of molybdenite of about the same magnitude as was found in these experiments for the sensibility maximum. While the evidence is far from conclusive, one is naturally led to look for some connection between the electrical and optical properties in selenium and stibnite. Bearing this in mind, it is to be remembered that only investigations of the optical and electrical properties which are carried out on the same sample, are comparable. If it should happen that a parallelism exists between the optical and electrical properties of these two substances,

[1] PHYS. REV., Vol. 1, series II, p. 237; PHYS. REV., Vol. 1, series II, p. 245.
[2] Pfund, PHYS. REV., XXVIII., No. 5, 1909.
[3] Nicholson, PHYS. REV., Vol. III., No. 1, 1914.
[4] Koenigsberger, Ann. d. Phys., Band 43, heft 8, p. 1205, 1914.
[5] Mueller, N. J. F. Min. Blbd. 17, 244, 1903.
[6] Trowbridge, PHYS. REV., Vol. II., No. 5, Nov., 1905.

then there can be no doubt that the mechanisms of absorption and increased conductivity are intimately connected.

SUMMARY.

To summarize the results of this paper:

1. A new form of selenium cell has been prepared particularly adapted for low temperature work.

2. Sensibility curves of selenium and stibnite at 20° C. and − 190° C. show that lowering the temperature causes: (*a*) A shift of the sensibility maximum towards the region of shorter wave-lengths by about 600 A.U. for both stibnite and selenium; (*b*) An extension of range of sensibility from 0.9 μ to at least 2 μ for both selenium and stibnite.

3. Sensibility curves for the same stibnite cell for both equilibrium exposures and exposures of ten seconds show a shift towards longer wave-lengths for the equilibrium exposures.

4. Investigation of the law connecting deflections and energy shows: (*a*) For equilibrium exposures, both stibnite and selenium obey the square root law, *i. e.*, $D = KE^{\beta}$ where-$\beta = 0.5$ approximately. (*b*) For stibnite at − 190° C., exposure ten seconds, $\beta = 0.77$.

5. Both selenium and stibnite show voltage effects.

6. These results seem to indicate that the mechanism which brings about light sensitiveness in selenium and stibnite is of the same general character.

In conclusion I wish to thank Professor J. S. Ames for suggesting the problem and for his interest throughout the investigation. To Professor A. H. Pfund for his many helpful suggestions and his constant encouragement I wish to express my sincere appreciation.

JOHNS HOPKINS UNIVERSITY,
May, 1914.

AN EXTENSION TOWARD THE ULTRA-VIOLET OF THE WAVE-LENGTH-SENSIBILITY CURVES FOR CERTAIN CRYSTALS OF METALLIC SELENIUM.

By L. P. Sieg and F. C. Brown.

IN a recent paper[1] we published a number of characteristic wave-length-sensibility curves for certain crystals of metallic selenium. We were unable with the apparatus then employed to carry our curves below wave-length .50 μ with any great degree of certainty, on account of the small amount of energy available from the Nernst glower in this region. We have recently employed a right angled arc, focusing the positive crater of the arc upon the slit. By means of this intrinsically brighter source we have been able to go to the limit of Hilger's monochromatic illuminator, .38 μ. A new instrument that will enable us to work in the ultra-violet region has been ordered, and as soon as it is received we propose to explore these crystals still further into this region. On account of the delay that may be involved at this time in getting this instrument we have thought it best to publish the work as far as we have carried it.

The apparatus employed was the same as that described in our previous paper[2] with the two exceptions of the arc light mentioned above, and a new Leeds and Northrup galvanometer substituted for the Siemens and Halske Panzer galvanometer. The arc light was much less steady than the Nernst glower, but by careful adjustment and attention we were able to get results that were sufficiently reliable to represent without question the true character of the curves. The D'Arsonval galvanometer was only slightly below the Panzer galvanometer previously used in working sensibility, but was vastly more steady in its action. Its resistance, and critical damping were each about 12 ohms, its sensibility 324 megohms, or 14.5 mm. per microvolt. The period was 7.3 sec. Adjustment for equal energy was made with a thermopile in just the same manner as in our previous work. Again the question whether equal energy falling upon these brilliantly reflecting crystals means equal absorbed energy among the various wave-lengths must be held in abeyance until some of their optical properties can be determined.

[1] Phys. Rev., 4, 1914, p. 507, 1914.

[2] Loc. cit.

The curves published in the former paper, to which this paper is an addendum, indicated in every case that the light sensibility was increasing as one proceeded below wave-length .50 μ. The indications pointed not only to an increase, but to a pretty sharp increase in sensibility. Our present work was done in the hope of locating a maximum in this region, but as far as we have gone the curves still rise, indicating the maximum, if there be any at all to be further into the ultra-violet. In the accompanying figure will be noted characteristic curves for two types of

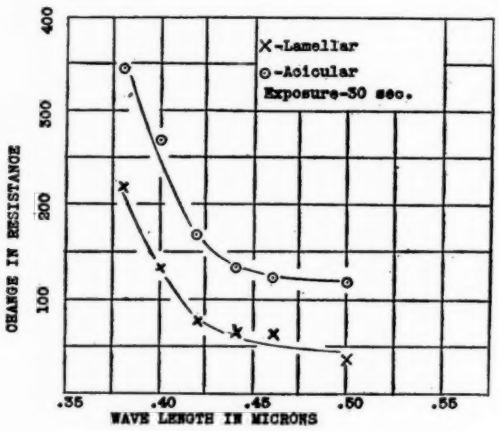

Fig. 1.

crystals, the lamellar and the acicular.[1] The former crystal was clamped between two conducting jaws and its thin edge was illuminated. The other crystal was similarly clamped, and was illuminated along its whole length a distance of about 7 mm. In both cases the action was what we called "direct," as distinguished from "transmitted" action. In other words, in this case, the light fell upon the conducting portion of the crystal. It should be noted that the energy used in these last experiments was about ten times as large as the energy employed in the work already referred to.

While it is unwise to make too close a comparison between the results from these crystals and those of work done on ordinary selenium cells,[2] it is interesting to note that although many of the characteristics are similar particularly with respect to light of the longer wave-lengths, there seems to be more of a difference when one deals with the shorter wave-lengths. For example we have thus far found no crystal that did

[1] For descriptions of these crystals, and for other references, see the paper previous to this; loc. cit. Also PHYS. REV. N. S., Vol. 4, p. 85, 1914.

[2] PHYS. REV., 4, 1914, p. 48.

not indicate an increase of sensibility toward the ultra-violet, whereas many of the cells tested showed a falling off in sensibility in this region. Nicholson[1] has carried some ordinary cells down to wave-length .23 μ, and has found a steady decrease in sensibility with the shorter-wave-lengths. As we noted above, however, there is no great value in making too close comparisons, because the peculiar mat, grey surface of the common selenium cell may react toward light in a manner decidedly different from that of these brilliant crystals.

It is interesting, even at the cost of going over old ground, to speculate upon what is going on in these crystals under light action. The increase in electric action toward the ultra-violet suggests a photo-electric effect. If that is the case then it becomes difficult to account for the maximum that appears in various places toward the red end of the spectrum. In the broad sense it is of course a photo-electric effect, only in this case it is not limited to the surface but takes place throughout the body of the crystal. And it must be remembered that it takes place through the crystal not only in the path of the light, but the action spreads to a distance, as we have already shown,[2] even going from the tip of a spine down into and through the main stem of a crystal cluster. If we are dealing here with the ordinary photo-electric effect, then we should find, when we proceed into the ultra-violet, no maximum whatever, but rather a steady increase in sensibility. It may be that there is a fundamental curve for the light-electric effect on the basis of Planck's theory which will show a steady increase in proceeding from the long to the short wave-lengths, and that the various maxima found in between will find their explanation in the common optical properties of these crystals, such as selective absorption, selective transmission, body color, etc. The fact that these peculiar maxima have thus far made their appearance in the red region of the spectrum, coupled with the fact that the color transmitted through these crystals is reddish in color may be of importance in the final solution. Work along this line is to be prosecuted at once.

Physical Laboratory,
State University of Iowa.

[1] Phys. Rev., 3, 1914, p. 1.
[2] Phil. Mag., 28, 1914, p. 497.

NOTE ON THE INDUCTION COIL SPARK.

BY WILL C. BAKER.

IT is well known that the spark of an induction coil following the "make" of the primary current is composed of a series of discharges; and similarly at "break." These are usually *assumed* to be oscillations in the secondary circuit consequent upon the single impulse due to the rise or to the fall of the current in the primary. The following observations show that, in certain coils at least, these partial sparks are not oscillatory but in each case consist of groups of unidirectional pulses.

An induction coil[1] capable of producing a 40-centimeter spark was energized from a 110-volt circuit through a variable resistance. The make and break was effected through an arm attached to a motor driven shaft, contact being made once every revolution with a fixed brush as in Feddersen's apparatus for the analysis of condenser sparks.[2] This rotating shaft carried also the metallic mirror in which the sparks were observed. The terminals of the secondary of the coil were attached to spherical brass electrodes, one of which was carried on a rack and pinion to enable the spark length to be adjusted. In order to suppress the explosions of metallic vapor studied by Battelli and Magri[3] and the "streamers" of Schuster and Hemsalech[4] the spheres were covered with cheese cloth kept wet with dilute sulphuric acid. The discharges thus took place between liquid electrodes.

Under these circumstances each partial spark shows a bright spot where it joins the cathode but none at the anode. This polarity enables one to see that the partial discharges at "make" are all in one direction and that the partial discharges at "break" are all in the opposite direction. The fact that the polarity of the discharges visibly reverses between "make" and "break" shows that there is no "valve action" in the system, for in that case one set or the other would be suppressed. This still leaves open the *possibility* that the current in the secondary may be of the nature of a small unidirectional current of relatively long duration and that as it raises the electrodes to sparking potential they

[1] Made by Queen and Co.

[2] Wiedemann, Lehre von der Elektricität, IV, 394.

[3] Sci. Abstr., *1671* (1907).

[4] Sci. Abstr., *1066* (1900); also Milner, Sci. Abs., *269* (1909).

discharge in a spark and are loaded up again time after time by the current. To show that the effect was not this result of the capacity of the electrodes, a small Geissler tube was put in the circuit between one electrode and the coil. An examination of the phenomena at the electrodes of the tube showed that the unidirectional pulses existed in the conductor leading to the spark gap. Even after cutting out the spark gap between the spheres so that the Geissler tube short-circuited the secondary of the coil the same result was obtained. These observations seem to show that the current delivered at the terminals of the secondary coil consists of a series of pulses as described above.

There are always fewer partials at "break" than at "make" owing to the arc formed at the interrupter in the former case. For short gaps at "make," twenty to fifty partials could be seen, but as the gap widened the number diminished to one or two. The first or "pilot" spark of one of these series was usually thick and of a brilliant spark white. This was followed by a series of purple "brush-light sparks,"[1] and these again by a set of thin spark white partials that closed the series. It seems that these purple sparks are carried by the ions left by the very energetic pilot spark, and when this ionization has decayed to a limit the third group obtains. These sparks do not seem to supply ions in quantities sufficient to compensate for the decay of those produced by the first spark. Often the final set, after its first or second white spark, may include one or two purple ones, and these in every case noted show the same polarity as the second set. This idea of the cause of the change in the nature of the sparks is supported by the fact that a current of air across the gap will reduce the purple sparks almost to zero, as the ions left by the pilot spark are swept away by the blast.

These partial sparks are not due to any vibration of the brush at the interrupter, as they persist unchanged with different types of brush and with a mercury break as well. A further proof of this is found in the fact that the same phenomena occur at break, *i. e.*, after all connection with the mains, brushes, etc., has been broken. The effect may be seen with a spark gap of two metal balls, but here the "streamers" and explosions of metallic vapor referred to above render it less prominent.

The Geissler tube in no case gave indications of these three stages of the sparks which fact bears out the idea given above, as the gas in tube is more easily ionized than that in the air gap.

The same phenomena, only on a smaller scale, were observed with a coil capable only of a 15-centimeter spark.[2]

[1] See Toepler, Ann. d. Physik, *2* (1900).

[2] From Gaertner and Co.

Beaded Sparks.

Under certain conditions the pilot spark shows a definite structure, being a thick spark white for two thirds of the way across and for the rest of the way a purple brush. The partial sparks exhibit also variations of intensity or "beads" suggesting strongly the beaded lightning of the meteorologist. These are best developed by putting in series with the Feddersen break, an electrolytic interrupter of the Wehnelt type. The one that gave the best effect was of platinum wire 0.25 mm. in diameter, projecting 3 mm. from the protecting glass. This arrangement gives strong partial sparks due to the sharp interruption of the Wehnelt. Using liquid terminals, as above, one finds, for spark lengths of 2 or 3 millimeters a bright pilot spark followed by a series of purple sparks. On widening the gap brilliant spark white spots appear on the partials, like white beads on a purple string. Sometimes three or four on a single partial. These are not due to harmonics or to superposition as in the cases reported on by Hemsalech[1] and by Léauté,[2] for they occur irregularly both in time and in position nor are they effects of gas set free from the electrodes as in the cases referred to by Battelli and Magri[3] for they exhibit no "trajectories" in the successive partials. They appear to be due to the irregular removal of the ions left from the previous discharge, the spark showing purple in those regions where sufficient ions remain to carry the discharge, and "sparking" across those regions from which the ions have been removed by the field, or by the irregular air disturbance due to the explosion of the preceding partial. The time interval from partial to partial was estimated, from observations of displacement of the image in the mirror, at about one five thousandth of a second.

This view of the cause of the spots is borne out by the following observations: While the wind from the rotating mirror seems to have no appreciable effect (plate glass shield), an air blast across the gap causes the beads to appear in a set of sparks otherwise wholly purple, the beads being longer as the blast is stronger. Thus with a gap of 6 or 7 millimeters one can pass, altering the air blast alone, from (1) a series of purple columns (for no blast); through (2) purple columns with one or more white beads; to the case where (3) the beads lengthen, leaving the purple shrunken to a few dark spots in a brilliant white column; and finally, with stronger blast still, to (4) full bright sparks with no dark spots at all. In the cases between (2) and (3) one can often see tiny ramified brushes extending through the purple from one white bead to

[1] Sci. Abs., *1140* (1908).
[2] Sci. Abs., *1291* (1908), and *277* (1909).
[3] Sci. Abs., *1671* (1907), and *137* (1910).

the next, just as though the beads were metal electrodes with a brush arc between them. Or when one finds a single white bead near the middle of the spark the brushes extend from the electrodes gathering in as they approach the bead from both sides.

This suggestion as to the origin of the beads receives further support from the fact that between stages (1) and (2) when only single beads are found on a few of the partials they are, *independently of the direction of the current, always opposite the smaller electrode*, where of course the field would remove the ions most rapidly. The beads were observed with the smaller coil as well. Interrupters of much larger carrying capacity than the one referred to above gave heavily mantled sparks with no beads, owing probably to the greater number of ions produced at each partial discharge. The necessary conditions for the beads seems to be a series of impulses bringing the electrodes sharply to disruptive potentials and recurring so quickly that each spark finds the partly ionized path of its predecessor.

PHYSICAL LABORATORY,
SCHOOL OF MINING,
QUEEN'S UNIVERSITY,
KINGSTON, ONT.,
September 2, 1914.

PROCEEDINGS

OF THE

AMERICAN PHYSICAL SOCIETY.

CHICAGO MEETING, NOVEMBER 27 AND 28, 1914.

MINUTES OF THE SEVENTY-FOURTH MEETING.

A REGULAR meeting of the Physical Society was held at Ryerson Laboratory, University of Chicago, Friday and Saturday, November 27 and 28, 1914. The Friday session was in charge of a local committee consisting of R. A. Millikan, A. A. Michelson, and Henry Crew. On Friday evening the Physical Society were the guests of the University of Chicago at the lecture of Professor W. H. Bragg of Leeds University, England.

Friday Afternoon, 2:00 P. M.

Symposium on Spectroscopic Evidence Regarding Atomic Structure. The following different aspects of the topic were presented:

The Nicholson Atom.....H. B. Lemon.
The Ritz Theory.....Henry Gale.
The Stark Effect.....G. S. Fulcher.
Energy Relations in Light Excitation by Impact...G. W. Stewart.
X-ray Spectra.....Karl Darrow.

Each topic was followed by a general discussion of about twenty minutes. Adjournment 5:45 P.M.

Friday Evening, 8:15 O'clock.

Lecture by Professor W. H. Bragg in Kent Theater on "X-ray Spectra and the Nature of X-rays." (Illustrated by slides and models.) Followed by reception at the Quadrangle Club.

Saturday Morning, 9:00 O'clock.

The Application of the Electron Theory to the Explanation of the Electrical Conduction in Crystals of Metallic Selenium. F. C. BROWN.

Some Fundamental Electro-mechanical and Photo-electrical Relations in Isolated Crystals of Selenium. F. C. BROWN.

Light-Sensibility Curves for Certain Crystals and Metallic Selenium, and their Significance. L. P. SIEG.

On the Reflecting Power of a Certain Selenium Crystal. L. P. SEIG.

Transmission of Sound Through Fabrics. F. R. WATSON.

A Differential Dynamic Method for the Accurate Determination of the Vapor Pressure Lowering of Solutions. E. W. WASHBURN.

A Method for Determining the Variation of Frequency of the Light Emitted with the Speed of the Source. G. S. FULCHER.

Note on the Polarization and Absorption of Light by a Narrow Slit in a Thick Screen. G. W. STEWART.

The Leading Characteristics of the Electric Furnace Spectra of Vanadium and Chromium. (By title.) ARTHUR S. KING.

Note on the Optical Constants of Nickel Cathode Films. L. R. INGERSOLL AND G. L. LUKE.

Determination of the Wave-length of Characteristic Roentgen Rays by Means of Diffraction and by the Photo-electric Effect. (By title.) OSCAR ALAN RANDOLPH.

Experiments on the Width of Spectral Lines. A. T. DEMPSTER.

Thermal Radiation. MAX MASON AND OTTO ZOBEL.

Radioactivity of Spring Water. R. R. RAMSEY.

Saturday Afternoon, 2:00 O'clock.

Spark Discharges Between Unlike Metals. DANIEL L. RICH.

The Arc in a Longitudinal Magnetic Field. (By title.) R. F. EARHART.

Thermal Capacity of Tungsten at Incandescent Temperatures, and an Apparent Lag of Radiation Intensity with Respect to Temperature. A. G. WORTHING.

A Method for the Determination of the Law of Variation of Mass with Velocity for Cathode Rays. L. T. JONES.

Saturation Value of the Intensity of Magnetization of an Iron-Cobalt Alloy. E. H. WILLIAMS.

The Direct Current Corona of a Wire Through a Circular Opening of a Disc. L. W. FAULKNER.

Experimental Determination of the Relation between the Corona Current and the Increase of Pressure due to D.C. Corona; Possibilities of a High Potential Voltmeter Based on this Pressure Phenomenon. (Presented by JAKOB KUNZ.) E. H. WARNER.

Determination of the Elementary Charge of Electricity by Means of Magnetic Properties and the Magneton. JAKOB KUNZ.

A Comparison of Simultaneous Measurements of Short Distances between Conducting Flats in Air, by the Optical Electrical Method. L. E. DODD.

The Law of Fall of a Droplet through Hydrogen. R. A. MILLIKAN AND W. H. BARBER.

The Variation of the Wave-Length Sensibility Curves of Selenium with Temperature. E. O. DIETERICH.

A New Form of Resistance Thermometer. (By title.) S. LEROY BROWN.

The Effect of Current and External Heating upon the Elasticity of a Mild Steel and an Aluminum Wire. H. L. DODGE.

Isolated Crystals of Metallic Selenium of the Second and Fifth Systems and the Physical Conditions determining their Production. F. C. BROWN.

At a brief business session, the following amendment to By-law No. II. presented October 31st at the New York meeting, was adopted:

"Replace the second sentence of the By-law as it now stands by the following: 'Each new Regular or Associate Member shall pay dues and receive Journals from the January first or July first next following his election.'"

This opportunity is taken of publicly recording the following extracts from the Minutes of the Council, a copy of which was transmitted to Mrs. Peirce in June, 1914, in regard to the death of our late President, B. O. Peirce:

"In view of the universal and genuine grief which has been felt and expressed by the members of the American Physical Society over the death of their late colleague and President, Benjamin Osgood Peirce, the Council of the Society is instructed to make the following minute:

"On the fourteenth day of January, 1914, we lost one of the original group of kindred spirits that banded together for the organization of this Society. His generous and genial personal traits had endeared him to all who knew him. His presence at any meeting went far to make that meeting a happy and successful event. His accurate and profound scholarship was an inspiration to each member. His advice was often sought and always welcomed.

"Remembering Professor Peirce so keenly as a dispenser of sunshine and help, we here make record of our loss. Sharing with his family a deep sense of bereavement, we request our Secretary to send to Mrs. Peirce the warm sympathy of this group of her husband's friends.

"HENRY CREW,
"EDWARD L. NICHOLS,
"ARTHUR GORDON WEBSTER,
"*Committee.*"

On motion, the thanks of the Association were extended to the University of Chicago for arranging Professor Bragg's lecture at the time of our meeting, and for other courtesies extended during the meeting.

A. D. COLE,
Secretary.

SOME FUNDAMENTAL ELECTRO-MECHANICAL, PHOTO-ELECTRICAL AND ELECTRICAL RELATIONS IN CRYSTALS OF METALLIC SELENIUM.[1]

BY F. C. BROWN.

1. Light of all portions of the visible spectrum alters the conductivity of crystals of metallic selenium of two systems.

2. When the light is removed the recovery is very rapid.

3. If the entire crystal is illuminated equilibrium is reached in less than 0.2 second.

[1] Abstract of a paper presented at the Chicago meeting of the Physical Society, November 28, 1914.

4. The maximum sensibility for given energy is in the ultra-violet.

5. The crystals are in equilibrium such that a pressure of 180 atmospheres will increase the conductivity a hundred fold.

6. The specific conductivity increases with the applied voltage.

7. The light-action may be transmitted almost undiminished throughout the crystal.

8. The pressure effect is not transmitted outside the region of the mechanical stress in the crystal.

9. The effect of the electric potential is not transmitted beyond the region of the electrical stress, nor does it manifest itself except in the direction of electrical field.

10. The absolute sensibility to light increases with pressure proportional to the conductivity in the dark.

11. This increased sensibility takes place only at the place where the pressure is applied.

12. This increase of sensibility holds for the transmitted light action as well as the direct action of light.

13. The velocity of transmission of the action at a distance by light is greater than two cm. per sec.

STATE UNIVERSITY OF IOWA,
IOWA CITY, IA.

THE APPLICATION OF THE ELECTRON THEORY TO THE EXPLANATION OF THE ELECTRICAL CONDUCTION IN CRYSTALS OF METALLIC SELENIUM.[1]

BY F. C. BROWN.

CRYSTALS of metallic selenium are peculiarly adapted for a test of the electron theory of conduction, because of the varied interrelated optical, mechanical and electrical properties. A large number of fundamental experiments have been carried out, which involve large changes in the electrical conductivity.

It is postulated that the nature of the conductivity is the same regardless of the physical conditions that have influenced it. Since the specific conductivity may vary several hundred per cent. by any one of several agencies, it is not conceivable that a variation in the free path or the velocity would sufficiently account for any of the changes. Rather a change in the number of conducting electrons must be expected to account for the varying conductivity.

To merely suppose an addition of free electrons as was first suggested by Pfund,[2] who likened the light-effect in selenium to an internal photoelectric effect is not sufficient. However recent experiments by Sieg and the writer[3] showing a maximum sensibility in the ultra-violet for selenium crystals call

[1] Abstract of a paper presented at the Chicago meeting of the Physical Society, November 28, 1914.

[2] PHYS. REV., Vol. 28, p. 324, 1909.

[3] PHYS. REV., N. S., 1915.

for further efforts to explain light action along the lines suggested by Pfund. The usual free electron hypothesis does not offer an explanation of the increase of light sensitiveness with pressure proportional to the conductivity in the dark. Second it will not explain why the change of conductivity by pressure or electrical fields is limited to the region of the crystal under stress. And third it will not explain why the increase of light-sensitiveness is limited to the region under pressure, and is practically unlimited as to what region of the crystal is illuminated.

The author is proposing a modified form of the electron theory that seems to satisfy all the fundamental experiments thus far recorded.[1] The view supposes that a large portion of the conducting electrons in the crystal are ordinarily fixed in the crystal structure in varying degrees of stability. When an electric field is established across the crystal a certain average number of these fixed electrons are rendered unstable or free. The divergence from the usually accepted notion is that they remain free only for a relatively short interval of time. Thus in these crystals we have the current increasing with voltage more rapidly than required by Ohm's law.

The effect of the increase of pressure is to lessen the degree of the stability so that the mean interval before the recombination of the electrons is increased. Obviously this seems to satisfactorily explain the increased light sensitiveness with increased pressure and the exact proportionality observed, and also the limitation of this increase to the region of the crystal under pressure. The transmitted light action observed by us[2] is probably a mechanical disturbance propagated in the crystal and enters into this theory only as the disturbance keeps electrons out of their fixed positions.

If it were not for this rapid recombination of the electrons the change of conductivity by pressure or electrical forces should be noticable throughout a given crystal structure. A study of the conductivity changes very near the region of applied pressures might give some information as to the rate of recombination of the electrons.

STATE UNIVERSITY OF IOWA,
IOWA CITY, IA.

THE EFFECT OF CURRENT AND EXTERNAL HEATING UPON THE ELASTICITY OF A MILD STEEL AND AN ALUMINUM WIRE.[3]

BY H. L. DODGE.

TESTS upon a sample of mild steel wire over a temperature range of 20° C. to 600° C. indicate a decrease of the Young's modulus at an increasing rate, the total change amounting to about 40 per cent. The nature of the change in the modulus of aluminum wire is the same although the rate of change

[1] PHYS. REV., N. S., 4, p. 85, 1914, and PHYS. REV. and Phil. Mag. (6), Vol. 28, p. 497.

[2] Phil. Mag., loc. cit.

[3] Abstract of a paper presented at the Chicago meeting of the Physical Society, November 28, 1914.

is much greater. A decrease in the modulus of 40 per cent. occurs with a temperature of about 170° C. Current heating has no effect other than that caused by the accompanying temperature. These results are similar to those secured with copper wire[1] and lead one to believe that further investigation may be expected to lead to the general law that the Young's modulus of metals decreases with increase of temperature at a rapidly increasing rate.

STATE UNIVERSITY OF IOWA.

DETERMINATION OF THE WAVE-LENGTH OF CHARACTERISTIC ROENTGEN RAYS BY MEANS OF DIFFRACTION AND BY THE PHOTOELECTRIC EFFECT.[2]

BY OSCAR ALAN RANDOLPH.

CHARACTERISTIC Roentgen rays have been isolated from an ordinary Roentgen ray by means of reflection from rock salt, gypsum and brucite, whose spectrograms will be presented. Attempts are being made of measuring the wave-length by 2 independent methods.

UNIVERSITY OF ILLINOIS,
URBANA, ILL.

DETERMINATION OF THE ELEMENTARY CHARGE OF ELECTRICITY BY MEANS OF MAGNETIC PROPERTIES AND THE MAGNETON.[2]

BY JAKOB KUNZ.

A MODIFICATION of the deduction of Langevin's theory of magnetism will first be presented. The average value of e has been found to be $1{,}53.10^{-20}$. Evidence in favor and against the magneton will be discussed. The periodic systems of the elements, their magnetic properties, the magneton and chemical valency will be considered.

UNIVERSITY OF ILLINOIS,
URBANA, ILL.

THE DIRECT CURRENT CORONA OF A WIRE THROUGH A CIRCULAR OPENING OF A DISC.[2]

BY L. W. FAULKNER.

IN connection with the investigation of S. P. Farwell[3] the corona of a wire through a circular opening in a metallic disc was investigated, in the first place with respect to its practical interest. A large number of interesting phenomena have been observed, especially transient phenomena between two different types of discharge under practically the same conditions as to voltage, pressure, etc. Under a certain pressure of 73 mm. Hg and 4,500 volts when the wire is negative, there appear two beads of light, one travelling up and down

[1] PHYS. REV., N. S., 2, 431, 1913.

[2] Abstract of a paper presented at the Chicago meeting of the Physical Society, November 28, 1914.

[3] PHYS. REV., 1914, and Proceedings of A. T. E. E.

the wire, the other moving round the circular disc. A large number of characteristic curves and power curves as function of the pressure have been taken. A small arc in series with the discharge tube affects very materially the nature of the phenomena.

UNIVERSITY OF ILLINOIS,
URBANA, ILL.

A COMPARISON OF SIMULTANEOUS MEASUREMENTS OF SHORT DISTANCES BETWEEN CONDUCTING FLATS IN AIR, BY THE OPTICAL-ELECTRICAL METHOD.[1]

BY L. E. DODD.

1. Using distances from 28½ to 7 lambda (Na) between conducting flats in air, it has been found that the combined optical and electrical method for measuring short distances (by counting interference bands, and by capacity measurements, respectively) give results showing a linear relationship, the slope of the resulting straight line being 45 degrees, and the line passing through the origin.

2. In the course of the work perfect insulation has been obtained down to seven wave-lengths, with electrodes in air.

3. This method furnishes an invariable determination of the zero point for work between electrodes at small distances, which the work of Rother lacks. In Rother's work the electrodes must first be brought into contact, which condition is assumed when large conduction occurs.

4. The present work differs from Rother's in that he used electrodes in vacua, while here the work has been carried on in air.

5. A possible doubt with regard to the work of Brown has been removed, confirming his results that showed good insulation at as low as two wave lengths of sodium light.

STATE UNIVERSITY OF IOWA,
IOWA CITY, IA.

[1] Abstract of a paper presented at the Chicago meeting of the Physical Society, November 28, 1914.

Experimental Determination of the Relation between the Corona Current and the Increase of Pressure Due to D.C. Corona; Possibilities of a High Voltmeter Based on this Pressure Phenomenon.[1]

By E. H. Warner.

IT has been shown by S. P. Farwell that at the instant the corona appears the pressure in the corona apparatus increases. In the Physical Review, Vol. 4, July, 1914, Mr. Farwell shows the relation of this increase in pressure and the difference of potential.

According to ionization theory the corona current should be directly proportional to this increase in pressure. To test this relation experiments have been performed upon dry air and nitrogen with potential differences up to 15,000 volts. With the wire positive it has been found that the current is directly proportional to the increase in pressure. With the wire negative the relation is direct for lower voltages but with higher voltages the pressure increases more than the current. In this case the currents are larger and therefore the heating effects more prominent. This variation from the direct proportion may be explained by the fact that, in the apparatus used the increase in pressure could not be measured before the current caused a temperature increase which added to the measured pressure increase.

Several attempts have been made to construct a high-potential voltmeter based upon this principle.

University of Illinois,
Urbana, Ill.

The Leading Characteristics of the Electric Furnace Spectra of Vanadium and Chromium.[1]

By Arthur S. King.

A STUDY of these spectra, similar to the previous ones for iron and titanium, has been made with the object of showing at what temperatures the various lines appear and the rate of increase in intensity as the temperature rises, the lines being classified on this basis.

The results show that at a certain temperature, apparently within 200° C. of its melting point, each element begins to show its spectrum, this consisting of a relatively small number of lines which are usually, but not always, among the strongest lines in the arc. At a higher temperature, the bulk of the distinctive arc lines are in evidence, while at the highest temperatures employed with the furnace (2600° to 2700° C.) the main change is in bringing out the weaker arc lines and a widening, with frequent reversals, of the stronger lines. With vanadium, as with titanium, the stronger of the lines peculiar to the spark spectrum are given faintly by the high-temperature furnace.

[1] Abstract of a paper presented at the Washington meeting of the Physical Society, November 28, 1914.

In reference to changes in the spectrum with wave-length, lines farther in the ultra-violet are given as the temperature rises, and the arc shows lines of shorter wave-length than the high-temperature furnace. No further resemblance to the intensity change in the spectrum of a solid body with temperature is observable, as low-temperature lines are distributed throughout the spectrum, many of them occurring in the blue and violet.

The tendency of lines to reverse in the furnace spectrum increases toward shorter wave-lengths, reversals being rare in the yellow and red, even among low-temperature lines.

The vanadium spectrum further resembles that of titanium in the large number of lines which are weak in the arc but are given strongly in the furnace. The reason for this is obscure. It appears to be due to differences other than temperature between the arc and the furnace.

The bands occurring in the arc spectra of vanadium and chromium are absent in the vacuum furnace. This indicates that they are probably due to oxides of the metals.

MOUNT WILSON SOLAR OBSERVATORY,
November 12, 1914.

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